

(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
16 January 2003 (16.01.2003)

PCT

(10) International Publication Number  
WO 03/005292 A1

(51) International Patent Classification<sup>7</sup>: G06K 11/14, 11/18, G01S 5/30, G01B 17/00, G06F 3/033

(21) International Application Number: PCT/GB02/03073

(22) International Filing Date: 3 July 2002 (03.07.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data: 0116310.4 4 July 2001 (04.07.2001) GB

(71) Applicant (for all designated States except US): NEW TRANSDUCERS LIMITED [GB/GB]; 37 Ixworth Place, London SW3 3QH (GB).

(72) Inventor; and

(75) Inventor/Applicant (for US only): SULLIVAN, Darius, Martin [GB/GB]; New Transducers Limited, Cygnet House Kingfisher Way, Hinchingbrooke Business Park, Huntingdon, Cambs PE29 6FW (GB).

(74) Agent: MAGUIRE BOSS; 5 Crown Street, St. Ives, Cambridgeshire PE27 5EB (GB).

(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

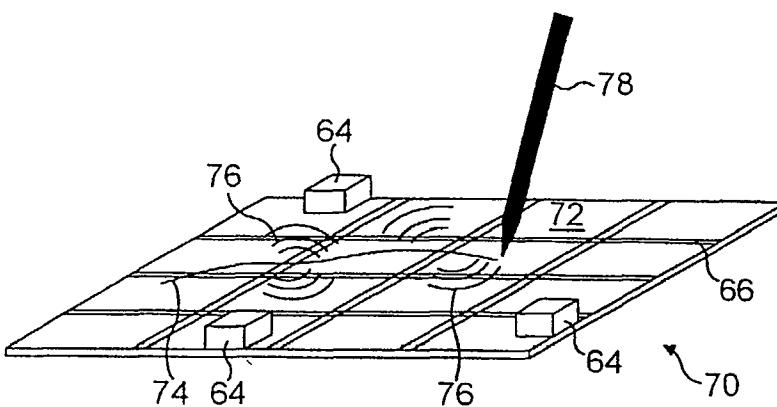
(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

## Published:

- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CONTACT SENSITIVE DEVICE



(57) Abstract: A contact sensitive device (10) comprising a member (12) capable of supporting bending waves, a first sensor (16) mounted on the member for measuring bending wave vibration in the member, the sensor (16) determining a first measured bending wave signal and a processor which calculates information relating to a contact on the member (12) from the measured bending wave signal, the processor applying a correction based on the dispersion relation of the material of the member (12) supporting the bending waves, characterised in that the device (10) comprises a second sensor (16) to determine a second measured bending wave signal which

WO 03/005292 A1

is measured simultaneously with the first measured bending wave signal and the processor calculates a dispersion corrected function of the two measured bending wave signals which is selected from the group consisting of a dispersion corrected correlation function, a dispersion corrected convolution function, a dispersion corrected coherence function and other phase equivalent functions to determine information relating to the contact.

5

TITLE: CONTACT SENSITIVE DEVICE

10

DESCRIPTION15 TECHNICAL FIELD

The invention relates to contact sensitive devices.

BACKGROUND ART

Visual displays often include some form of touch sensitive screen. This is becoming more common with the 20 emergence of the next generation of portable multimedia devices such as palm top computers. The most established technology using waves to detect contact is Surface Acoustic Wave (SAW), which generates high frequency waves on the surface of a glass screen, and their attenuation by the 25 contact of a finger is used to detect the touch location. This technique is "time-of-flight", where the time for the

disturbance to reach one or more sensors is used to detect the location. Such an approach is possible when the medium behaves in a non-dispersive manner i.e. the velocity of the waves does not vary significantly over the frequency range of interest.

5 In contrast in WO01/48684 to the present applicant, a contact sensitive device and method of using the same are proposed. The device comprises a member capable of supporting bending wave vibration and a sensor mounted on the member for measuring bending wave vibration in the member and for  
10 transmitting a signal to a processor whereby information relating to a contact made on a surface on the member is calculated from the change in bending wave vibration in the member created by the contact.

By bending wave vibration it is meant an excitation, for  
15 example by the contact, which imparts some out of plane displacement to the member. Many materials bend, some with pure bending with a perfect square root dispersion relation and some with a mixture of pure and shear bending. The dispersion relation describes the dependence of the in-plane  
20 velocity of the waves on the frequency of the waves.

Two types of contact sensitive device are proposed, namely a passive sensor in which bending wave vibration in the member is only excited by the contact and an active sensor in which the contact sensitive device further comprises an  
25 emitting transducer for exciting bending wave vibration in the member to probe for information relating to the contact. In

the active sensor, information relating to the contact is calculated by comparing the response of waves generated by the emitting transducer in the absence of a contact to the response caused by the mechanical constraint of the presence 5 of a contact.

Bending waves provide advantages, such as increased robustness and reduced sensitivity to surface scratches, etc. However, bending waves are dispersive i.e. the bending wave velocity, and hence the "time of flight", is dependent on 10 frequency. In general, an impulse contains a broad range of component frequencies and thus if the impulse travels a short distance, high frequency components will arrive first. This effect must be corrected.

In WO01/48684, a correction to convert the measured 15 bending wave signal to a propagation signal from a non-dispersive wave source may be applied so that techniques used in the fields of radar and sonar may be applied to detect the location of the contact. The application of the correction is illustrated in Figures 1a to 1d.

20 Figure 1a shows an impulse in an ideal medium with a square root dispersion relation and demonstrates that a dispersive medium does not preserve the waveshape of an impulse. The outgoing wave (60) is evident at time  $t=0$  and the echo signal (62) is spread out over time, which makes a 25 determination of an exact contact position problematic.

In a non-dispersive medium such as air, a periodic variation of the frequency response is characteristic of a reflection, and is often referred to as comb filtering. Physically, the periodic variation in the frequency response derives from the number of wavelengths that fit between the source and the reflector. As the frequency is increased and the number of wavelengths fitting in this space increases, the interference of the reflected wave with the outgoing wave oscillates between constructive and destructive.

Calculating the Fourier transform of the dispersive impulse response of Figure 1a produces the frequency response shown in Figure 1b. The frequency response is non-periodic and the periodic variation with wavelength translates to a variation in frequency that gets slower with increasing frequency. This is a consequence of the square root dispersion in which the wavelength is proportional to the square root of the inverse of frequency. The effect of the panel on the frequency response is therefore to stretch the response as a function of frequency according to the panel dispersion. Consequently, a correction for the panel dispersion may be applied by applying the inverse stretch in the frequency domain, thus restoring the periodicity present in the non-dispersive case.

By warping the frequency axis with the inverse of the panel dispersion, Figure 1b may be transformed into the frequency response for the non-dispersive case (Figure 1c) in

which the frequency of excitation is proportional to the inverse of the wavelength. This simple relationship translates the periodic variation with decreasing wavelength to a periodic variation with increasing frequency as shown in 5 Figure 1c.

Applying the inverse Fast Fourier Transform (fft) to the trace of Figure 1c produces an impulse response shown in Figure 1d which is corrected for dispersion and where the clear reflection is restored. As is shown in Figure 1d any 10 particular waveshape of an impulse is preserved in time since the waves travelling in a non-dispersive medium have a constant velocity of travel, independent of their frequency. Accordingly, the task of echo location is relatively straight forward. The outgoing wave (50) is evident at time  $t=0$ , 15 together with a clear reflection (52) at 4ms. The reflection (52) has a magnitude which is approximately one-quarter of the magnitude of the outgoing wave (50).

The procedure described is not applicable if the impulse has occurred at an unknown time  $t_0$  and the distance  $x$  from the 20 response to an initial impulse may only be calculated if the impulse occurs at  $t_0 = 0$ .

It is an object of the present invention to provide an alternative contact sensitive device which uses bending wave vibration for extracting information relating to the contact.

25 DISCLOSURE OF INVENTION

According to one aspect of the invention, there is

provided a contact sensitive device comprising a member capable of supporting bending waves, a first sensor mounted on the member for measuring bending wave vibration in the member, the first sensor determining a first measured bending wave 5 signal and a processor which calculates information relating to a contact on the member from the measured bending wave signal, the processor applying a correction based on the dispersion relation of the material of the member supporting the bending waves, characterised in that the device comprises 10 a second sensor to determine a second measured bending wave signal which is measured simultaneously with the first measured bending wave signal and the processor calculates a dispersion corrected function of the two measured bending wave signals which is selected from the group consisting of a 15 dispersion corrected correlation function, a dispersion corrected convolution function, a dispersion corrected coherence function and other phase equivalent functions to determine information relating to the contact.

According to a second aspect of the invention, there is 20 provided a method of determining information relating to a contact on a contact sensitive device comprising the steps of providing a member capable of supporting bending waves and a first sensor mounted on the member for measuring bending wave vibration in the member, determining, using the sensor, a 25 first measured bending wave signal characterised by providing a second sensor mounted on the member to determine a second

measured bending wave signal, measuring the second measured bending wave signal simultaneously with the first measured bending wave signal, calculating a dispersion corrected function of the two measured bending wave signals which is  
5 selected from the group consisting of a dispersion corrected correlation function, a dispersion corrected convolution function, a dispersion corrected coherence function and other phase equivalent functions and processing the measured bending wave signals to calculate information relating to the contact  
10 by applying the dispersion corrected function.

The following features may be applied to both the device and the method with the processor being adapted to provide many of the calculations or processing steps of the method.

15 The dispersion corrected function may be calculated as follows:

calculate  $\hat{W}_1(\omega)$  and  $\hat{W}_2(\omega)^*$  which are the Fourier transformation and complex conjugate Fourier transformation of the two measured bending wave signals  $W_1(t)$  and  $W_2(t)$ ;  $t$  represents time  $\omega$  is  $2\pi f$  where  $f$  is frequency.

20 calculate a first intermediate function  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$ ;

calculate a second intermediate function  $M(\omega)$  which is a function of  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$ ;

apply a frequency stretching operation  $f(\omega)$ , as described above in relation to WO01/48684, to  $M(\omega)$  to give the  
25 dispersion corrected correlation function:

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} M[f(\omega)] \exp(i\omega t) d\omega .$$

The intermediate function  $M(\omega)$  may simply be  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$  which gives a standard dispersion corrected correlation function. Alternatively,  $M(\omega)$  may be a function which modifies 5 the amplitude but not the phase of  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$  to give a phase equivalent function to the standard dispersion corrected correlation function. Since the phase equivalent function and the standard dispersion corrected correlation function have the same phase properties, they have a maximum at the same 10 position. The phase information in the measured bending wave signals may be used to acquire information about the contact in particular the location thereof. The location may be calculated from the time at which the maximum in the functions occurs.

15  $M(\omega)$  may be selected from the following functions which all yield phase equivalent functions to the standard dispersion corrected correlation function:

$$a) M(\omega) = \frac{\hat{W}_1(\omega)\hat{W}_2^*(\omega)}{|\hat{W}_1(\omega)\hat{W}_2^*(\omega)|}$$

Thus  $M(\omega)$  may normalise the amplitudes of  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$  to 20 unity to yield a normalised dispersion corrected correlation function otherwise known as a dispersion corrected coherence function.

$$b) M(\omega) = \frac{\hat{W}_1(\omega)\hat{W}_2^*(\omega)}{\sqrt{|\hat{W}_1(\omega)\hat{W}_2^*(\omega)|}}$$

Thus  $M(\omega)$  may act on the amplitudes of  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$  to yield a dispersion corrected correlation function with a modified peak shape.

5 c)  $M(\omega) = \hat{W}_1(\omega)\hat{W}_2^*(\omega)\varphi\left|\hat{W}_1(\omega)\hat{W}_2^*(\omega)\right|$  where  $\varphi(x)$  is a real valued function

Thus  $M(\omega)$  may apply a general modification to yield a phase equivalent function having a different amplitude to the standard correlation function.

10 d)  $M(\omega) = \hat{W}_1(\omega)\hat{W}_2^*(\omega)\psi(\omega)$  where  $\psi(\omega)$  is a real valued function

Thus  $M(\omega)$  may apply a general frequency-dependent scaling to yield a phase equivalent function having a different amplitude to the standard correlation function. Such a 15 scaling is also known as emphasis.

Alternatively,  $M(\omega)$  may be the function  $\hat{D}(\omega)$  which is the Fourier transformation of the correlation function  $D(t)$ :

$$D(t) = \int_{-\infty}^{\infty} W_1(t+t')W_2(t')dt'$$

$\hat{D}(\omega)$  is mathematically equivalent to  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$  and may 20 be arrived at without calculating  $\hat{W}_1(\omega)$  and  $\hat{W}_2(\omega)^*$ . This is an alternative method to calculating the standard dispersion corrected correlation function. The steps are calculate  $D(t)$ ;

calculate  $\hat{D}(\omega)$  and apply a frequency stretching operation to arrive at the dispersion corrected correlation function:

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{D}[f(\omega)] \exp(i\omega t) d\omega.$$

One advantage of using the dispersion corrected correlation function is that it is applicable in situations where the precise time,  $t_0$ , at which a contact occurred is not known. This is because an offset  $t_0$  (i.e.  $t_0 \neq 0$ ) in the response functions is represented as an additional factor  $\exp(i\omega t_0)$  in the Fourier transformations,  $\hat{W}_1(\omega)$  and  $\hat{W}_2(\omega)$  which cancels in the intermediate function  $\hat{W}_1(\omega)\hat{W}_2^*(\omega)$ .

A transducer may act as both the first and second sensor whereby, the dispersion corrected correlation function is an autocorrelation function. The autocorrelation function may be calculated applying the same steps for the dispersion corrected correlation function using  $W_1(t) = W_2(t)$ .

The frequency stretching operation may be determined as described in relation to Figures 1a to 1d by  $\hat{\Omega}(\omega) = \hat{W}[f(\omega)]$  in which  $f(\omega)$  is chosen so that  $\hat{\Omega}(\omega)$  represents an imaginary response of a medium where bending waves of all frequencies travel with identical phase velocity. For example, for bending mode vibrations that follow a square-root relation of wavevector,  $k$ , to angular frequency,  $k = C\sqrt{\omega}$ , the frequency stretching operation  $f(\omega) = \nu C\sqrt{\omega}$  gives an imaginary response,

$\Omega(t)$ , of a medium with constant arbitrary phase velocity  $v$ .  $C$  is a constant and is defined by  $C=(\mu/B)^{1/4}$  where  $\mu$ =mass per unit area, and  $B$ =bending stiffness.

The inverse Fourier transform,  $\Omega(t)$  may be examined to 5 determine the distance to the site of the contact.  $\Omega(t)$ , is centred at a value  $t_1$  that is proportional to the distance between the site of the contact and each sensor.

The dispersion corrected correlation function may also be used to determine the precise location of the contact. For 10 example, for the function,  $G(t)$ , the centre of the correlation function is located at  $t=(x_1-x_2)/v$  where  $x_1$  and  $x_2$  are the distances from the contact point to the respective vibration sensors. The dispersion corrected correlation function may therefore be used to determine a difference in path-length 15 (i.e.  $x_1-x_2$ ) between the contact site and the two sensors.

This quantity,  $x_1-x_2$ , defines a hyperbola of possible locations of the contact on the panel surface. If a third sensor is provided, a second dispersion corrected correlation function, from a different combination of sensor positions, 20 provides a second path-length difference, eg.  $x_1-x_3$ .

Alternatively, a second pair of sensors may be mounted to the member to provide a second dispersion corrected correlation function. In many cases (for example when the sensors are positioned in the four corners of a rectangular panel), the 25 two hyperbolic curves defined by the two path-length

differences have a unique intersection point which determines unambiguously the location of the contact.

Another advantage of using the dispersion corrected correlation function is in the treatment of waves reflected from boundaries of the member. The reflected waves create the effect of virtual sources which are located outside the physical boundaries, specifically, at the contact site reflected in the axes of the boundaries. The impulse generated by a contact may show features corresponding to 'echoes' which arrive after the direct waves of the impulse. By applying the dispersion correction to an impulse at  $t=0$ , discrete reflections may be resolved as peaks in the corrected impulse response. The location of these peaks may be used as additional information for determining the location of the contact. This may be particularly effective if the sensitivity, or acceptance, of the sensors is not independent of the direction of the incoming wave since the measured signal corresponding to the direct path from the contact may be weaker than the signal due to reflected waves.

The dispersion-corrected autocorrelation function may be applied to locate the path-length difference between the sensor and real and virtual sources of bending waves arising from reflections at the boundaries. Such information may help the determination of the contact location.

Reflected waves may be suppressed by placing an absorbing material in contact with the edges of the member.

Alternatively, the processor may be adapted to remove the contribution of reflected waves from the measured bending wave signal. This may be achieved on the basis that in a dispersive medium, i.e. one with a dispersion relation of the form

5  $k = C\sqrt{\omega}$ , low-frequency components travelling along the direct path may arrive after the first high-frequency reflected waves. This processor may be adapted to provide a moving average low-pass filtering operation on the original measured bending wave signal where the width of the averaging window

10 varies locally with the time coordinate as  $\Delta t \propto t^2$ .

The measured bending wave signal may be transformed to a response in which the signals due to the direct and reflected wave both oscillate with constant but different periods. For example, a measured bending wave signal  $W(t)$ , from a contact

15 at time  $t=0$  may be transformed on the time axis by using  $U(\tau) = W(1/\tau)$ . In the function  $U(\tau)$  the signal from a sharp impulse propagating on a dispersive member oscillates with a constant period. Furthermore, the oscillations from the direct wave have a longer period than those of the reflected waves.

20 The contribution of reflected waves can therefore be removed by a low pass filter operation on  $U(\tau)$ . The response may then be transformed back to linear units of time, as  $W'(t) = U(1/t)$ . The procedure may be generalised to other forms of the dispersion relation.

25 For a perfect rejection of reflected waves, it is

necessary to know the dispersion relation in the member, the time  $t_0$  at which the contact occurred, and the distance  $x$  between the contact site and the sensor. However, generally, only the first is known. Thus the processor may be adapted to 5 provide estimates or substitutes for  $t_0$  and  $x$  which may be substituted into a calculation to remove the reflected waves. For example, an estimate for  $t_0$  may be the time at which the contact was first detected by any sensor on the member, i.e. the time at which the measured signal first passes a 10 predetermined threshold. The distance  $x$  may be set as the distance between the relevant sensor and the furthest point on the member or the maximum dimension (e.g. diameter) of the member. Use of these substitutes should leave the direct-path signal intact. Estimates of  $t_0$  and  $x$  obtained by other means 15 may also be used.

There may be multiple (i.e.  $n$ ) sensors on the member and thus the number of distinct correlation functions is  $n(n-1)/2$ . The processor may be adapted to create a mapping function which maps the surface of the member for each correlation 20 function whereby the dispersion corrected correlation function,  $G(t)$ , is swept over the surface such that all co-ordinates of a given path-length difference,  $\Delta x$ , take the value  $G(\Delta x/v)$ . The product of the entire set of mapped correlation functions may then be calculated and the location 25 of the contact may be determined from the maximum co-ordinate.

This method has the desired property of increasingly rejecting spurious contributions from reflections as the number of sensors is increased.

Each sensor and its associated circuitry may have 5 identical or different phase properties. Differences in the phase properties may be caused by mechanical inconsistencies in the manufacture and mounting of the sensors, or by finite tolerances of component values in the associated amplification and filtering circuits. If the phase properties of each 10 sensor differ, the dispersion corrected correlation function may be convolved with some asymmetric function. This asymmetric function may lead to incorrect measurements of path-difference difference since the position of peaks in the dispersion corrected correlation function is no longer 15 independent of the phase properties of the sensor.

The processor may thus be adapted to perform the following steps:

a) estimate a convolution correction coefficient  $\phi_{12}(\omega)$  from

$$\phi_{12}^*(\omega) = \left| \sum_j \hat{W}_{1,j}(\omega) \hat{W}_{2,j}^*(\omega) \exp[-ik(\omega)\Delta x_j] \right|$$

20 where  $\{\hat{W}_{1,j}(\omega)\}$  and  $\{\hat{W}_{2,j}^*(\omega)\}$  are the Fourier transformation and complex conjugate Fourier transformation of two measured bending wave signals  $\{W_{1,j}(t)\}$  and  $\{W_{2,j}(t)\}$  and  $\{\Delta x_j\}$  is the path-length difference;

b) calculate the dispersion corrected correlation function 25 with phase correction from:

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{W}_1[f(\omega)] \hat{W}_2^*[f(\omega)] \phi_{12}[f(\omega)] \exp(i\omega t) d\omega .$$

The phase correction has the effect of deconvolving the dispersion corrected correlation function such that the position of the maximum is consistent with the position of the contact.

5 The processor may further be adapted to include in the determination procedure any available information about where the contact can be expected. This may be particularly useful in situations where the position of a contact may not be unambiguously determined by the dispersion corrected  
10 correlation functions, e.g. when reflected waves interfere with the direct-wave signature or less than three sensors are used. For example, if the member is an input device for a graphical user interface where the user is presented with a choice of 'buttons' to press, it may be useful to assume that  
15 any contact on the member occurs within the discrete areas corresponding to the buttons.

Alternatively, a map of the probability at which a contact is likely to occur and which is based on the expected behaviour of the user may be used. The device may comprise a  
20 software application with a graphical user interface (GUI) which interacts with the operating system by means of an application program interface (API) in which the API is adapted to generate the probability map. The probability map may be based on the location, size, and frequency of use of

objects presented by the graphical user interface. The probability map may also be based on information about the relative likelihood of the various GUI elements being activated.

5        The information in the mapped correlation functions may be combined with the probability map to give higher reliability. The expected probability may also be a further input to a neural-net which accepts information derived from the sensors.

10       The member may comprise a raised pattern on its surface whereby a contact drawn across the surface provides a variable force to the member to generate bending waves in the member. The pattern may be periodic, or quasi-periodic with a statistically well-defined spatial distribution of 15 undulations. The processor may be adapted to determine the contact position by using knowledge of the periodicity of the pattern and the fact that the interval between impulses represents the time in which a contact, which may be provided by a stylus, has travelled to an adjacent feature of the 20 pattern. The pattern may be random whereby a contact travelling over the surface of the member generates a random bending wave signal.

The use of random surface pattern may be used independently of the dispersion correction correlation 25 function. Thus according to another aspect of the invention, there is provided a contact sensitive device comprising a

member capable of supporting bending waves, a sensor mounted on the member for measuring bending wave vibration in the member to determine a first measured bending wave signal and a processor which calculates information relating to the contact 5 from the measured bending wave signal from the sensor, characterised in that a surface of the members comprises a raised pattern whereby a contact drawn across the surface provides a variable force to the member to generate bending waves in the member.

10 The device may comprise sensing means to determine a second measured bending wave signal which is measured simultaneously with the first measured bending wave signal and the processor may calculate information relating to the contact from a dispersion corrected correlation function of 15 the two measured bending wave signals. The dispersion corrected correlation function is described above and thus features of the first and second embodiments may be applied to this embodiment. The dispersion corrected correlation function is particularly useful if the measured bending wave 20 signals have a large bandwidth centred on a frequency which gives a phase-velocity of bending waves in the member which is much greater than the maximum lateral velocity of the contact.

According to another aspect of the invention, there is provided a contact sensitive device comprising a member 25 capable of supporting bending waves, a sensor mounted on the member for measuring bending wave vibration in the member to

determine a first measured bending wave signal and a processor which calculates information relating to a contact from the measured bending wave signal from the sensor, characterised in that the device comprises at least a second sensor to

5 determine a second measured bending wave signal which is measured simultaneously with the first measured bending wave signal and the processor optimises a product of a set of corrected impulse response measurements from each sensor to determine information related to the contact.

10 The information calculated may be the time  $t_0$  at which contact occurs and thus the form of the dispersion relation,  $k(\omega)$ , and the distance,  $x$ , separating each sensor from the contact site must be known. The corrected impulse response measurement may be calculated by using the following steps:

15 1) Calculate the Fourier transform  $\hat{W}(\omega)$  of a measured bending wave signal  $W(t)$ ;

2) Calculate an equivalent response,  $W'(t)$ , from a notional sensor positioned at the contact site by

$$\hat{W}'(\omega) = \hat{W}(\omega) \exp[ik(\omega)x].$$

3) Calculate the inverse Fourier transform of  $\hat{W}'(\omega)$  to provide

20 function  $W'(t)$ .

The product is thus  $\prod_j W'_j(t)$  in which the function  $W'(t)$  shows an initial impulse from the contact which is without dispersion and which is centred at  $t_0$ , the time of the impulse. Features in  $W(t)$  due to edge reflections will appear

later in  $W'(t)$  but will not be corrected for dispersion in the same way as for the direct impulse which is thus more easy to identify.

The product shows a strong peak due to the direct impulse, and a weak background noise. By taking the product we reinforce the signal coincident at  $t_0$  in all  $W'_j(t)$ , whereas the information due to reflections is uncorrelated and suppressed. This procedure is therefore a reliable way of determining  $t_0$ .

Conversely, the information relating to the contact may be the location of the contact, i.e. the co-ordinate  $r$  and thus the sensor-contact distances,  $x_j$  and the time  $t_0$  for which the maximum value of  $\prod_j W'_j(t_0)$  is obtained must be known.

This optimisation process may involve iterative refinement of estimates for  $r$  and  $t_0$ . The initial estimate may be derived from impulse response functions whose high temporal frequency components have been suppressed, with the result that the estimate is easy to obtain (fewer local maxima), but of low spatial precision. Further iterations may introduce progressively higher frequency components as the estimate is refined.

The invention therefore provides two complementary methods of determining the contact position: the method of dispersion-corrected correlation functions, and the method of maximising  $\prod_j W'_j(t_0)$ .

The following characteristics may apply to all

embodiments of the invention. The device may comprise means for recording measured bending wave signals from the or each sensor over time as the contact moves across the member. The measured bending wave signals may be recorded as time-series 5 data, i.e. a sequence of values measured at different times.

The time-series data may be analysed as a sequence of short sections or 'frames' of data, which may have widths or durations of 10ms. The processor may apply a window function to the frames of data. Window functions are well known in the 10 art - see for example Press W.H. et al., *Numerical Recipes in C*, 2 Ed., Cambridge University Press 1992, Ch. 13.4. The processor may be adapted to extract information on the contact which has been averaged over the duration of the frame, e.g. the mean positional co-ordinate of the moving contact. The 15 processor may apply the dispersion corrected correlation technique to calculate the mean path length difference for each frame of data to give a sequence of path-length differences over time.

Alternatively, the time-series data may be analysed using 20 adaptive filters such as those described in Grant PM et al "Analogue and Digital Signal Processing and Coding", Ch 10 (1989). The adaptive filter may correct for a convolution function which relates the time-series data from the first and second measured bending wave signals. The convolution function 25 changes slowly over time as the contact moves and is dependent on the position of the contact.

The adaptive filter may calculate a convolution correction which when applied to the measured bending wave signals produces a signal as close as possible to the measurement input. The first measured bending wave signals 5 form a first time-series data which may be sent to the reference signal of the adaptive filter and the second measured bending wave signals form a second time-series data which may be delayed, preferably by the maximum expected width of the correlation function, before being sent to the primary 10 input of the adaptive filter whereby the convolution correction may be calculated. The processor may apply the dispersion correction to the convolution function to give a function whose maximum is determined by the difference between the path-length from contact to the sensor and the path-length 15 from the contact to the sensing means.

The information calculated may be the location of the contact or may be other information, e.g. pressure or size of the contact. The information relating to the contact may be calculated in a central processor. The sensors may be mounted 20 at or spaced from an edge of the member. The sensors may be in the form of sensing transducers which may convert bending wave vibration into an analogue input signal.

The member may be in the form of a plate or panel. The member may be transparent or alternatively non-transparent, 25 for example having a printed pattern. The member may have uniform thickness. Alternatively, the member may have a more

complex shape, for example a curved surface and/or variable thickness. The processor may be adapted for complex shaped members by providing an adaptive algorithm such as a neural net to decipher the contact location from the bending wave 5 signal received by the sensor.

The device may be a purely passive sensor with the bending wave vibration and hence the measured bending wave signals being generated by an initial impact or by frictional movement of the contact. Alternatively, the device may be an 10 active sensor and thus the device may comprise an emitting transducer. The transducer may have dual functionality, namely acting as an emitting transducer and a sensor. The member may also be an acoustic radiator and bending wave vibration in the member may be used to generate an acoustic output.

15 Measurements of the bending wave signal due to a contact may be contaminated by the bending waves due to the audio signal, particularly when the audio signal is similar to the bending wave signal generated by the contact. The effect may be minimised by ensuring the frequency band of the audio 20 signal differs from and does not overlap the frequency band of the measurements from the sensors and sensing means. The audio and measured signals may thus be filtered, for example, the audio band may be limited to frequencies below 20kHz, and the vibration measurements may be limited to frequencies above 25 20kHz.

The device may be a dual active and passive sensor and

may be adapted to switch between active and passive sensing modes depending on whether contact is applied to the device. The device may cycle between resting in passive sensing mode when no contact is detected, switching to active mode sensing 5 when a contact is applied and returning to passive sensing mode once the contact is removed to wait for further contacts. This may be advantageous to avoid the power drain when the device is in active mode.

The contact may be in the form of a touch from a stylus 10 which may be in the form of a hand-held pen. The movement of a stylus on the member may generate a continuous signal which is affected by the location, pressure and speed of the stylus on the member. The stylus may have a flexible tip, e.g. of rubber, which generates bending waves in the member by 15 applying a variable force thereto. The variable force may be provided by tip which alternatively adheres to or slips across a surface of the member. As the tip moves across of the member a tensile force may be created which at a certain threshold, causes any adhesion between the tip and the member 20 to break, thus allowing the tip to slip across the surface.

Alternatively, the contact may be in the form of a touch from a finger which may generate bending waves in the member which may be detected by passive and/or active sensing. The bending waves may have frequency components in the ultrasonic 25 region (>20 kHz). Passive sensing is therefore sensitive to contacts with both fingers and styli.

When the device is acting as an active sensor, i.e. with an emitting transducer generating an excitation signal, the contact may exert a non-linear force on the member so as to generate harmonics of the excitation signal. The processor may 5 comprise signal processing devices to isolate the excitation signal from the harmonics so that the harmonics may be used to determine the contact position in a similar manner to passive sensing. The harmonics effectively constitute a source of bending waves from the contact site.

10 The or each emitting transducer or sensor may be a bender transducer which is bonded directly to the member, for example a piezoelectric transducer. Alternatively, the or each emitting transducer or sensor may be an inertial transducer which is coupled to the member at a single point. The inertial 15 transducer may be either electrodynamic or piezoelectric. It may be possible to use audio transducers which are already in place as sensing and/or emitting transducers.

A contact sensitive device according to the invention may be included in a mobile phone, a laptop or a personal data 20 assistant. For example, the keypad conventionally fitted to a mobile phone may be replaced by a continuous moulding which is touch sensitive according to the present invention. In a laptop, the touchpad which functions as a mouse controller may be replaced by a continuous moulding which is a contact 25 sensitive device according to the invention. The moulding may be implemented as a mouse controller or other alternatives,

e.g. a keyboard. Alternatively, the contact sensitive device may be a display screen, e.g. a liquid crystal display screen comprising liquid crystals which may be used to excite or sense bending waves. The display screen may present 5 information relating to the contact.

#### BRIEF DESCRIPTION OF DRAWINGS

The invention is diagrammatically illustrated, by way of example, in the accompanying drawings, in which:-

Figures 1a to 1d are a graphic illustration of a method 10 of dispersion correction according to the prior art, in which

Figure 1a is a graph of a dispersive impulse response showing response in arbitrary units against time. Figure 1b is a graph of a dispersive frequency response showing response in arbitrary units against frequency. Figure 1c is a graph of a 15 non-dispersive frequency response showing response in arbitrary units against frequency. Figure 1d is a graph of a non-dispersive impulse response showing response in arbitrary units against time;

Figure 2 is a plan view of a contact sensitive device 20 according to the present invention;

Figure 3 is a perspective view of a first device incorporating passive touch sensing;

Figure 4 is a perspective view of a second device incorporating passive touch sensing;

25 Figure 5 is a block diagram of a processing algorithm for the passive sensing of Figures 3 and 4;

Figure 6 is a perspective view of first device incorporating active touch sensing;

Figure 7 is a perspective view of a second device incorporating active touch sensing;

5 Figure 8 is a flow chart showing a method of calculating the path-length difference between the contact and two measurement points using the dispersion corrected correlation function;

10 Figure 8a is a schematic plan view of a device to which the method of Figure 8 is applied;

Figure 8b is a graph of dispersion corrected correlation function against time;

Figure 9 is a flow chart showing a first method of removing reflections from a measured bending wave signal,

15 Figure 10 is a flow chart showing a second method of removing reflections from a measured bending wave signal.

Figure 11a and 11b are schematic perspective and plan views of a touch sensitive device according to another aspect of the invention;

20 Figure 12 is a schematic block diagram of a processing algorithm which may be used for the device of Figure 11.

Figure 12a is a graph showing the combined transfer function  $H(f)$  against frequency  $(f)$  for the filter and amplifier of Figure 12;

25 Figure 12b is a graph of a measured bending wave signal against time;

Figure 13 is a flow chart of the steps for obtaining an empirical phase correction;

Figure 13a is a plan view of a grid defined on a member for use in the method of Figure 13;

5 Figure 14 is a touch sensitive device according to another aspect of the invention;

Figure 15 is a circuit diagram of an adaptive noise canceller which may be used in the various devices;

10 Figure 16a is a schematic block diagram of a contact sensitive device which also operates as a loudspeaker;

Figure 16b is a method of separating audio signal and measured bending wave signal in the device of Figure 16a;

15 Figure 17 is a flow chart showing a method of calculating the contact location using the dispersion corrected auto-correlation function;

Figure 17a is a schematic plan view of a device to which the method of Figure 17 is applied;

Figure 17b is a graph of dispersion corrected auto-correlation function against time, and

20 Figure 18 is a block diagram showing how an adaptive filter may be used to calculate information relating to the contact.

Figure 2 shows a contact sensitive device (10) comprising a transparent touch sensitive plate (12) mounted in front of a display device (14). The display device (14) may be in the form of a television, a computer screen or other visual

display device. A stylus (18) in the form of a pen is used for writing text (20) or other matter on the touch sensitive plate (12).

The transparent touch sensitive plate (12) is a member, 5 e.g. an acoustic device, capable of supporting bending wave vibration. Three transducers (16) are mounted on the plate (12). At least two of the transducers (16) act as sensors or sensing means and are thus sensitive to and monitor bending wave vibration in the plate. The third transducer (16) may 10 also be a sensing transducer so that the system corresponds to the passive contact sensitive device of Figure 3 or Figure 4.

Alternatively, the third transducer may be an emitting transducer for exciting bending wave vibration in the plate so that the system corresponds to the active sensor of Figure 5. 15 In the Figure 6 or Figure 7 embodiment, the active sensor may act as a combined loudspeaker and contact sensitive device.

Figures 3 and 4 are more detailed illustration of two contact sensitive devices (32,33). The contact sensitive devices (32,33) comprises a member in the form of a panel (24) 20 capable of supporting bending wave vibration and three sensors in the form of sensing transducers (26) for sensing bending wave vibration at their respective mounting points. The vibration pattern (28) is created when pressure is applied at a contact point (30). The devices may be considered to be 25 passive contact sensitive devices since the devices do not comprise an emitting transducer. Thus the bending wave panel

vibration in the panel is generated solely by the contact.

In a passive sensor an impulse in the body of the panel (24) starts a bending wave travelling towards the edge of the panel (24). The bending wave is detected by the three sensing transducers (26) mounted equidistantly around the edges as in Figure 3 or by the three sensing transducer mounted on a surface of the panel (24) but spaced from the edges of the panel (24) as in Figure 4. The measured bending wave signals are processed to determine the spatial origin and force profile of the applied impulse.

Figure 5 shows a possible implementation for the processing of the bending wave information sensed at each sensing transducer (26) of Figure 3 or Figure 4. In Figure 5, the bending waves in the panel are sensed by three sensing transducers (26). The sensing transducers (26) measure analogue bending wave signals  $W_1(t)$ ,  $W_2(t)$  and  $W_3(t)$  which are transmitted to a multiplexing analogue to digital converter (ADC) (54). The resultant digital input signal is transmitted to the central processor (34) from which information (58) relating to the location and profile of the contact impulse is determined.

Figures 6 and 7 are more detailed illustrations of alternative combined touch sensitive and audio devices (35,37). The devices each comprise a panel (24) capable of supporting bending wave vibration and an emitting transducer (31) for exciting bending wave vibration in the panel (24).

The device (35) in Figure 6 further comprises two sensing transducers (26) for sensing bending wave vibration at their respective mounting points whereas the device (37) in Figure 7 comprises only one sensing transducer (26). The vibration 5 pattern (28) is interrupted when pressure is applied at a contact point (30). The devices may be considered to be active contact sensitive devices since the devices comprise an emitting transducer (31).

In Figure 6, the sensing and emitting transducers (26,31) 10 are spaced equidistantly around the edges of the panel (24) whereas in Figure 7, the sensing and emitting transducers (26,31) are distanced from the edges of the panel (24) and are mounted to a surface thereof.

Figure 8a shows an embodiment having two sensors (102) 15 mounted on a member (100) to which a contact is applied at a contact location (104). Figure 8 shows a method of calculating the dispersion corrected correlation function to reveal the difference in path length between the contact location (104) and the sensors (102). The method comprises the following 20 steps:

- (a) Measure two bending wave signals  $W_1(t)$  and  $W_2(t)$ ;
- (b) Remove reflections from the measured signals and calculate  $W'_1(t)$  and  $W'_2(t)$ , e.g. by using the method set out in Figure 9;
- (c) Calculate the Fourier transform of  $W'_1(t)$  and  $W'_2(t)$  to 25 arrive at  $\hat{W}_1(\omega)$  and  $\hat{W}_2(\omega)$  and hence the intermediate function

$\hat{W}_1(\omega) \hat{W}_2^*(\omega)$  ; where  $\hat{W}_2^*(\omega)$  is the complex conjugate Fourier transform.

(d) and (e) at the same time as performing steps (a) to (c), the frequency stretching operation  $f(\omega) = vC\sqrt{\omega}$  is calculated

5 using the predetermined panel dispersion relation  $k = C\sqrt{\omega}$ .

(f)  $\hat{W}_1(\omega)$  and  $\hat{W}_2(\omega)$  and  $f(\omega) = vC\sqrt{\omega}$  are combined to arrive at the dispersion corrected correlation function:

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{W}_1[f(\omega)] \hat{W}_2^*[f(\omega)] \exp(i\omega t) d\omega ; \text{ and}$$

(g) the dispersion corrected correlation function is plotted 10 against time with a peak occurring at time  $t_{12}$  as shown in Figure 8b;

(h)  $\Delta x_{12}$  is calculated from  $t_{12}$ ;  $\Delta x_{12}$  is the path-length difference between the path lengths  $x_1$  and  $x_2$  from the first and second sensors to the contact.

15 (i)  $\Delta x_{12}$  is used to calculate the location of the contact.

Alternatively at step (e), the dispersion corrected correlation function with phase correction  $\phi_{12}$  set out below may be used. The calculation of  $\phi_{12}$  is explained in Figure 13.

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{W}_1[f(\omega)] \hat{W}_2^*[f(\omega)] \phi_{12}[f(\omega)] \exp(i\omega t) d\omega$$

20 Figure 9 shows a method of removing reflections from an impulse measurement where the impulse occurs at  $t=0$ . The method comprises the following steps:

i) Measure a bending wave signal  $W_1(t)$ ;

- ii) Transform the signal on the time axis by using  $U(\tau) = W(1/\tau)$ ;
- iii) A low pass filter is applied, for example,  $U'(\tau)$  as shown to remove all reflected signals. The constant  $C$  from the predetermined panel dispersion relation  $k = C\sqrt{\omega}$  is used to

5 define the width of the convolution function  $\Delta\tau$ ;

- iv) The response may then be transformed back to linear units of time, as  $W'(t) = U(1/t)$ .

Figure 10 shows an alternative method for removing reflections from an impulse measurement where the impulse

10 occurs at  $t=0$ . The method comprises the following steps:

- i) Measure a bending wave signal  $W_1(t)$ ;
- ii) Estimate the distance  $x$  between each sensor and the location of the contact;
- iii) Use the estimate  $x$  and a predetermined dispersion

15 relation  $k = C\sqrt{\omega}$  to define an averaging window  $N(t, t')$

- iv) Apply the averaging window  $N(t, t')$  to the bending wave signal  $W_1(t)$  to remove the effect of reflections.

$N(t, t')$  is an example of an averaging window with a Gaussian shape. A rectangular window can be implemented to

20 give computational efficiency. Multiple applications of a rectangular window may be desirable; a large number of repeated applications of a rectangular window will produce a similar result to  $N(t, t')$ .

Figures 11a and 11b show a contact sensitive device (80)

25 comprising a rectangular member (82) capable of supporting

bending waves and four sensors (84) for measuring bending wave vibration in the member. The sensors (84) are in the form of piezoelectric vibration sensors and are mounted on the underside of the member (82), one at each corner. A foam 5 mounting (86) is attached to the underside of the member and extends substantially around the periphery of the member. The foam mounting (86) has adhesive surfaces whereby the member may be securely attached to any surface. The foam mounting may reduce the reflections from the edge of the member.

10 Two sets of path length differences,  $\Delta x_{12}=x_1-x_2$  and  $\Delta x_{34}=x_3-x_4$  are calculated as described in Figure 8;  $x_i$  is the distance from each sensor to the contact. As shown in Figure 11b the hyperbolae (85) defined by the two path-length differences are plotted and the location of the contact is the 15 intersection (87) of two hyperbolae.

Figure 12 is a schematic diagram illustrating the implementation of a processing algorithm in the device of Figure 11. The sensors (84) measure analogue bending wave signals  $W_1(t)$ ,  $W_2(t)$  and  $W_3(t)$  which are passed through an 20 amplifier and anti-aliasing (low-pass) filter (88). The amplitude of the combined transfer function  $H(t)$  of the amplifier and anti-aliasing filter is shown in Figure 12a. The filtered signals are converted into digital signals by a digitiser (90) and stored in a first-in-first-out buffer 25 having finite length. The buffer comprises two stores, a pre-trigger and a post-trigger store (92,93) for signals measured

before and after the detection process is triggered respectively.

The central processor (94) determines information relating to the location and profile of a contact of the member by the 5 following steps:

- a) The central processor performs a threshold test which is illustrated in Figure 12b. The measured bending wave signal (96) is compared to a predetermined threshold value (98). When the measured signal passes the threshold 10 value, the detection process is triggered.
- b) An array of time-series digital input signals is transferred from the buffer to the processor. The signals include measurements taken before and after the detection process is triggered so that a digital measure of the 15 entire waveform of the impulse from the contact is reconstructed.
- c) The processor shifts the waveform according to the estimate of  $t_0$  so that  $t_0$  is set to zero.
- d) The processor removes the effect of reflections from the 20 digitised signal as described above with the estimate of  $t_0$  as zero and the estimate of  $x$  taken as the diagonal length of the member.
- e) The processor applies further processing, in particular calculating the dispersion corrected correlation function 25 for each diagonally opposed pair of sensors and calculating information relating to the contact.

The further processing applied by the processor may also comprise applying a pre-determined phase correction to the dispersion corrected correlation function. This may be calculated as shown in Figure 13.

5 a) Define a grid - for example, for the embodiment shown in Figures 11a and 11b which has a member (82) which four sensors (84), this may be done by defining points (71) by the vector  $\{r_j\}$ . In this example the grid has 8 rows and 7 columns so the grid is defined by a set of 56 vectors  $[r_1, r_2 \dots r_{56}]$ .

10 b) A user taps on the first point (71) in the grid defined by  $r_1$  and the first and second bending wave signals  $\{W_{1,j}(t)\}$  and  $\{W_{2,j}(t)\}$  are measured by the first and second sensor of each pair of sensors;

15 c) Step (b) is repeated until the user has tapped on each point in the grid;

d) Calculate the Fourier transforms of the bending wave signals;

e) Calculate the empirical phase correction:

$$20 \phi_{12}^*(\omega) = \left| \sum_j \hat{W}_{1,j}(\omega) \hat{W}_{2,j}^*(\omega) \exp[-ik(\omega) \Delta x_j] \right|$$

where  $\Delta x_j$  is the difference between the path lengths,  $x_{1,j}$  &  $x_{2,j}$  from the first and second sensors to the contact. The path lengths are known from the grid coordinates.

Figure 14 shows a contact sensitive device (70) comprising a member (72) capable of supporting bending waves

and three sensors (64) mounted on the member for measuring bending wave vibration in the member. A surface of the member (72) comprises a raised pattern (66) which is a periodic pattern of raised crossed lines. A stylus (78) is drawn across 5 the surface along a path (74) and as it crosses a line of the pattern it generates bending waves (76) in the member.

Figure 15 shows an adaptive noise canceller for example as described in "Widrow et al Adaptive Noise Cancelling: Principles and Applications, Proceedings of the IEEE, Vol 63 10 No 12 pp 1692 (1975)". The adaptive noise canceller comprises an adaptive filter (40) which takes the initial audio signal as the reference input. The canceller may be used to remove the contribution of the audio signal from the output of a vibration sensor before any further processing occurs. The 15 adaptive filter shown is one example of an adaptive filter that can be applied to this task.

Figure 16a shows a contact sensitive device which also operates as a loudspeaker. Figure 16b shows a method for partitioning the audio signal and measured signal into two 20 distinct frequency bands so that the contribution of the audio signal to the processed measured signal is suppressed. The device comprises a member (106) in which bending waves are generated by an emitting transducer or actuator (108) and the contact. The emitting transducer applies an audio signal to 25 the member (106) to generate an acoustic output. Before being applied to the member, the audio signal is filtered by a low

pass filter (112) which, as shown in Figure 16b, removes the audio signal above a threshold frequency  $f_0$ .

As shown in Figure 16b, the contact generates a signal which has a power output which is substantially constant over 5 a large frequency band. The signal from the contact and the audio signal sum to give a combined signal which is passed through a high pass filter (114) to remove the signal above the threshold frequency  $f_0$ . The filtered signal is then passed to a digitiser (116) and onto a processor (118).

10 Figure 17a shows an embodiment having a single sensor (120) mounted on a member (100) to which a contact is applied at a contact location (104). Bending waves are reflected from the edge of the member and create an image of a virtual source which is at location (122). Figure 17 shows a method of 15 calculating the dispersion corrected auto-correlation function to reveal the contact location (104). The method comprises the following steps:

- (a) Measure one bending wave signal  $W_1(t)$ ;
- (b) Calculate the Fourier transform of  $W_1(t)$  to arrive at 20  $\hat{W}_1(\omega)$ ;
- (c) at the same time as performing steps (a) and (b), the frequency stretching operation  $f(\omega) = vC\sqrt{\omega}$  is calculated using the predetermined panel dispersion relation  $k = C\sqrt{\omega}$ .
- (d)  $\hat{W}_1(\omega)$  and  $f(\omega) = vC\sqrt{\omega}$  are combined to arrive at the 25 dispersion corrected auto-correlation function:

$$G(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{W}_1[f(\omega)] \hat{W}_2^*[f(\omega)] \exp(i\omega t) d\omega ; \text{ and}$$

(g) the dispersion corrected correlation function is plotted against time with peaks occurring at time  $t_{11}$  and  $-t_{11}$  as shown in Figure 17b;

5 (h)  $\Delta x_{11}$  is calculated from  $t_{11}$ ;  $\Delta x_{12}$  is the path-length difference between the path lengths  $x_1$  and  $x_1'$  from the first and second sensors to the contact.

(i)  $\Delta x_{12}$  is used to calculate the location of the contact.

Figure 18 shows the adaptive filter of Figure 15 may also 10 be used to calculate the location of the contact from a device comprising two sensors. In general, adaptive filters contain a finite-impulse-response (FIR) filter. A FIR filter is equivalent to a convolution operation, with some convolution function  $\Phi(t)$ .

15 The signals  $W_1(t)$  measured by the first sensor are sent to the adaptive filter (40) and the signals  $W_2(t)$  measured by the second sensor are sent to a delay unit (41). The delay unit delays the signals from the second sensor, preferably by the maximum expected width of the convolution function. The 20 delayed signals are then sent to the primary input of the adaptive filter. The adaptive filter continually updates the convolution function so that an estimate,  $\tilde{W}_2(t)$ , of the primary signal input,  $W_2(t)$ , may be obtained from the reference input,  $W_1(t)$ . The convolution operation is defined as follows:

$$\tilde{W}_2(t) = \int_{-\infty}^t W_1(t') \Phi(t-t') dt'.$$

The location of the contact is calculated in the processor by the following steps:

- a) Extract the FIR convolution function from the internal  
5 memory of the adaptive filter.
- b) Calculate the Fourier transform of the FIR convolution  
function.
- c) Apply the frequency stretching operation  $f(\omega) = vC\sqrt{\omega}$ ;
- d) Calculate the inverse Fourier transform to arrive at  $F(t)$ .

10  $F(t)$  is a phase equivalent of the dispersion correction correlation function  $G(t)$  and thus the Fourier transforms of  $G(t)$  and  $F(t)$  have equal phase but not necessarily the same amplitude. Accordingly, the location of any peaks in the time domain for  $F(t)$  and  $G(t)$  are the same and thus the location of  
15 the contact may be calculated from the peak of  $F(t)$  as described above for  $G(t)$ .

CLAIMS

1. A contact sensitive device comprising a member capable of supporting bending waves, a first sensor mounted on the member for measuring bending wave vibration in the member, the sensor determining a first measured bending wave signal and a processor which calculates information relating to a contact on the member from the measured bending wave signal, the processor applying a correction based on the dispersion relation of the material of the member supporting the bending waves, characterised in that the device comprises a second sensor to determine a second measured bending wave signal which is measured simultaneously with the first measured bending wave signal and the processor calculates a dispersion corrected function of the two measured bending wave signals which is selected from the group consisting of a dispersion corrected correlation function, a dispersion corrected convolution function, a dispersion corrected coherence function and other phase equivalent functions to determine information relating to the contact.
- 20 2. A contact sensitive device according to claim 1, wherein the first sensor acts as the second sensor whereby the calculated dispersion corrected function is an autocorrelation function.
3. A contact sensitive device according to claim 1 or claim 25 2, comprising a second pair of sensors to determine two additional measured bending wave signals from which a second

dispersion corrected function is calculated.

4. A contact sensitive device according to claim 3, wherein the processor determines from each dispersion corrected function a first difference in path-length between the contact site and each of the first and second sensors and a second difference in path-length between the contact site and each of the second pair of sensors and determines the location of the contact from the first and second differences in path-length.

5. A contact sensitive device according to any preceding claim, comprising absorbers mounted around at least part of the periphery of the member to absorb reflected waves.

6. A contact sensitive device according to any preceding claim, wherein the processor is configured to remove the contribution of reflected waves from the measured bending wave signal.

7. A contact sensitive device according to claim 6, wherein the processor comprises a low-pass filtering operator which operates on the measured bending wave signal and which comprises an averaging window having a width which varies locally with time.

8. A contact sensitive device according to claim 6 or claim 7, wherein the processor is configured to provide an estimate for the distance between the contact site and each sensor, the estimate being substituted into a calculation to remove the reflected waves.

9. A contact sensitive device according to any preceding

claim, comprising multiple sensors on the member whereby multiple dispersion corrected functions are determined.

10. A contact sensitive device according to claim 9, wherein the processor is configured to create a mapping function which 5 maps the surface of the member for each dispersion corrected function.

11. A contact sensitive device according to any one of the preceding claims, wherein the member is an acoustic radiator and an emitting transducer is mounted to the member to excite 10 bending wave vibration in the member to generate an acoustic output.

12. A contact sensitive device according to claim 11, comprising means ensuring that the acoustic output and measured bending wave signals are in discrete frequency bands.

15 13. A contact sensitive device according to claim 12, comprising an adaptive noise canceller for removing the contribution of the acoustic output from the measured bending wave signal.

14. A contact sensitive device according to any one of the 20 preceding claims, wherein the member is transparent.

15. A contact sensitive device according to any one of the preceding claims, wherein the processor estimates a convolution correction coefficient which is applied to the dispersion corrected function thereby compensating for phase 25 differences between the sensors.

16. A contact sensitive device according to any one of the

preceding claims, wherein the member comprises a raised pattern on its surface whereby a contact drawn across the surface provides a variable force to the member to generate bending waves in the member.

5 17. A contact sensitive device according to claim 16, wherein the pattern is random whereby random bending wave vibration is generated in the member.

18. A contact sensitive device according to any one of the preceding claims, comprising means for recording sets of first 10 and second measured bending wave signals from the or each sensor over time as the contact moves across the member.

19. A contact sensitive device according to claim 18, wherein the processor is adapted to analyse the measured bending wave signals as a sequence of frames of data.

15 20. A contact sensitive device according to claim 18, wherein the processor is adapted to extract information on the contact which has been averaged over the duration of the frame.

21. A contact sensitive device according to any one of the preceding claims, wherein the processor comprises an adaptive 20 filter which calculates a convolution function between the set of first measured bending wave signals and the set of second measured bending wave signals.

22. A contact sensitive device according to claim 21, wherein the processor is adapted to use a dispersion corrected 25 convolution function to calculate information about the contact.

23. A method of determining information relating to a contact on a contact sensitive device comprising the steps of

providing a member capable of supporting bending waves and a first sensor mounted on the member for measuring bending

5 wave vibration in the member,

determining, using the sensor, a first measured bending wave signal characterised by

providing a second sensor mounted on the member to determine a second measured bending wave signal,

10 measuring the second measured bending wave signal simultaneously with the first measured bending wave signal,

calculating a dispersion corrected function of the two measured bending wave signals which is selected from the group consisting of a dispersion corrected correlation function, a dispersion corrected convolution function, a dispersion corrected coherence function and other phase equivalent functions and

15 processing the measured bending wave signals to calculate information relating to the contact by applying the dispersion corrected function.

24. A method according to claim 23, wherein the dispersion corrected correlation function is calculated by the following steps:

25 calculate the Fourier transformation and complex conjugate Fourier transformation of the two measured bending wave signals;

calculate an intermediate function by multiplication of the Fourier transformation and complex conjugate Fourier transformation of the two bending wave signals;

combine a frequency stretching operation and subsequent 5 inverse Fourier transformation with the intermediate function to give the dispersion corrected correlation function.

25. A method according to claim 23, wherein a phase equivalent function is calculated by the following steps:

calculate the Fourier transformation and complex 10 conjugate Fourier transformation of the two measured bending wave signals;

calculate a first intermediate function by multiplication of the Fourier transformation and complex conjugate Fourier transformation of the two bending wave signals;

15 calculate a second intermediate function which is a function of the intermediate function;

combine a frequency stretching operation and subsequent inverse Fourier transform with the second intermediate function to give the phase equivalent function.

20 26. A method according to claim 25, wherein the second intermediate function is calculated by normalising the first intermediate function to give the dispersion corrected coherence function.

27. A method according to any one of claims 24 to 26, 25 comprising removing the effect of reflections before calculating the or each intermediate function.

28. A method according to any one of claims 23 to 27, comprising using the dispersion corrected function to determine a difference in path-length between the contact site and each sensor and hence to determine the location of the 5 contact.

29. A method according to any one of claims 23 to 28, comprising providing a transducer which acts as both the first and second sensor and calculating a dispersion corrected autocorrelation function.

10 30. A method according to any one of claims 23 to 29, comprising providing a second pair of sensors to determine two additional measured bending wave signals from which a second dispersion corrected function is calculated.

15 31. A method according to claim 30, comprising determining from each dispersion corrected function a first difference in path-length between the contact site and each of the first and second sensors and a second difference in path-length between the contact site and each of the second pair of sensors and determining the location of the contact from the first and 20 second differences in path-length.

32. A method according to any one of claims 23 to 31, comprising removing the contribution of reflected waves from each measured bending wave signal by operating a low-pass filtering operation on the measured bending wave signals.

25 33. A method according to any one of claims 23 to 31, comprising providing multiple sensors on the member whereby

multiple dispersion corrected functions are determined.

34. A method according to claim 33, comprising creating a mapping function which maps the surface of the member for each dispersion corrected function.

5 35. A method according to any one of claims 23 to 34, comprising calculating a convolution correction coefficient and applying the convolution correction coefficient when calculating the dispersion corrected function to compensate for any phase differences between the sensors.

10 36. A method according to any one of claims 23 to 35, comprising recording a set of first measured bending wave signals and a set of second measured bending wave signals from the or each sensor over time as the contact moves across the member.

15 37. A method according to claim 36, comprising analysing the sets as a sequence of frames of data.

38. A method according to claim 37, comprising extracting information relating to the contact from each frame which has been averaged over the duration of the frame.

20 39. A method according to claim 37 or claim 38, comprising correcting for a convolution function between the sets.

40. A contact sensitive device comprising a member capable of supporting bending waves, a sensor mounted on the member for measuring bending wave vibration in the member to determine a first measured bending wave signal and a processor which calculates information relating to a contact from the measured

bending wave signal from the sensor, characterised in that the device comprises at least a second sensor to determine a second measured bending wave signal which is measured simultaneously with the first measured bending wave signal and 5 the processor optimises a product of a set of corrected impulse response measurements from each sensor to determine information related to the contact.

41. A contact sensitive device according to claim 40, wherein the corrected impulse response measurement is calculated by 10 using the following steps:

Calculate the Fourier transform of the measured bending wave signal;

Calculate an equivalent response from a notional sensor positioned at the contact site

15 Calculate the inverse Fourier transform of the equivalent response to provide a function to be optimised.

42. A contact sensitive device according to claim 41, wherein the optimisation process involve iterative refinement of estimates of the location of the contact and the time for 20 which the maximum value of the product is obtained.

43. A contact sensitive device according to claim 42, wherein an initial estimate is derived from impulse response functions whose high frequency components have been suppressed.

44. A contact sensitive device comprising a member capable of 25 supporting bending waves, a sensor mounted on the member for measuring bending wave vibration in the member to determine a

first measured bending wave signal and a processor which calculates information relating to the contact from the measured bending wave signal from the sensor, characterised in that a surface of the members comprises a raised pattern 5 whereby a contact drawn across the surface provides a variable force to the member to generate bending waves in the member.

45. A contact sensitive device according to claim 44, wherein the pattern is periodic.

46. A contact sensitive device according to claim 45, wherein 10 the pattern is quasi-periodic with a statistically well-defined spatial distribution of undulations.

47. A contact sensitive device according to any one of claims 40 to 46, wherein the processor is configured to determine the contact position by using knowledge of the periodicity of the 15 pattern and the fact that the interval between impulses represents the time in which a contact has travelled to an adjacent feature of the pattern.

48. A contact sensitive device according to any one of claims 1 to 22 and 40 to 48, wherein the device is a purely passive 20 sensor with the bending wave vibration and hence the measured bending wave signals are generated by an initial impact or by frictional movement of the contact.

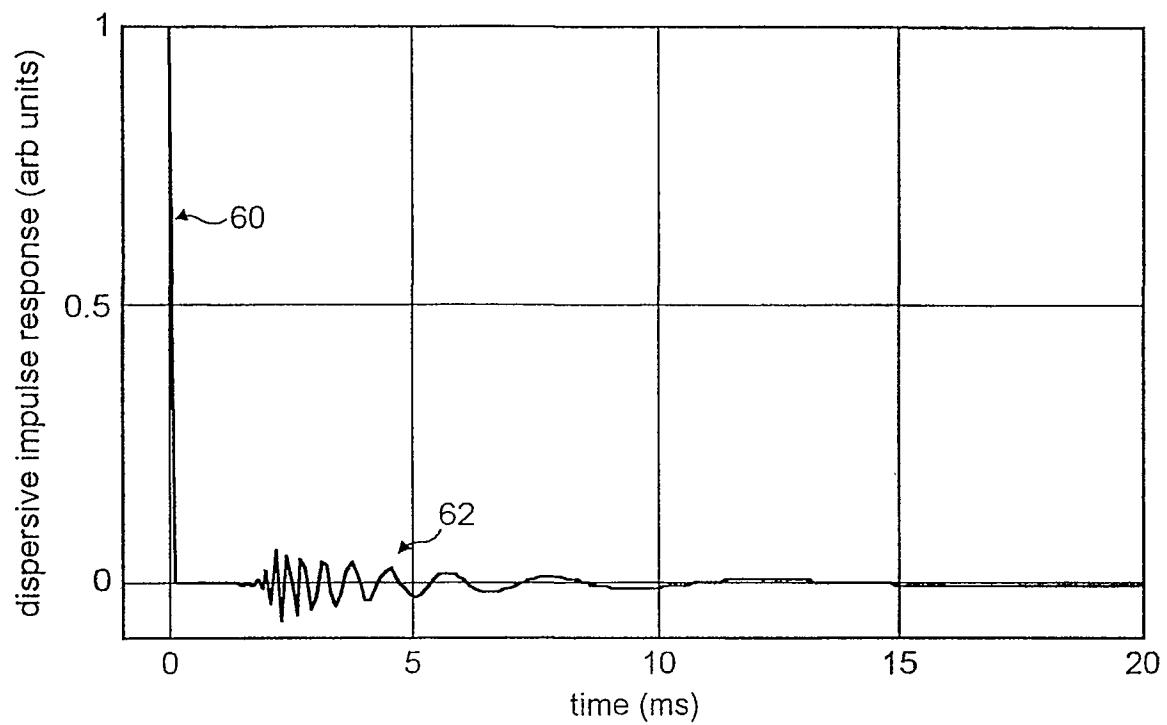
49. A contact sensitive device according to any one of claims 1 to 22 or 40 to 48, wherein the device is an active sensor 25 comprising an emitting transducer.

50. A contact sensitive device according to claim 48 or claim

49, wherein the device is a dual active and passive sensor and is configured to switch between active and passive sensing modes depending on whether contact is applied to the device.

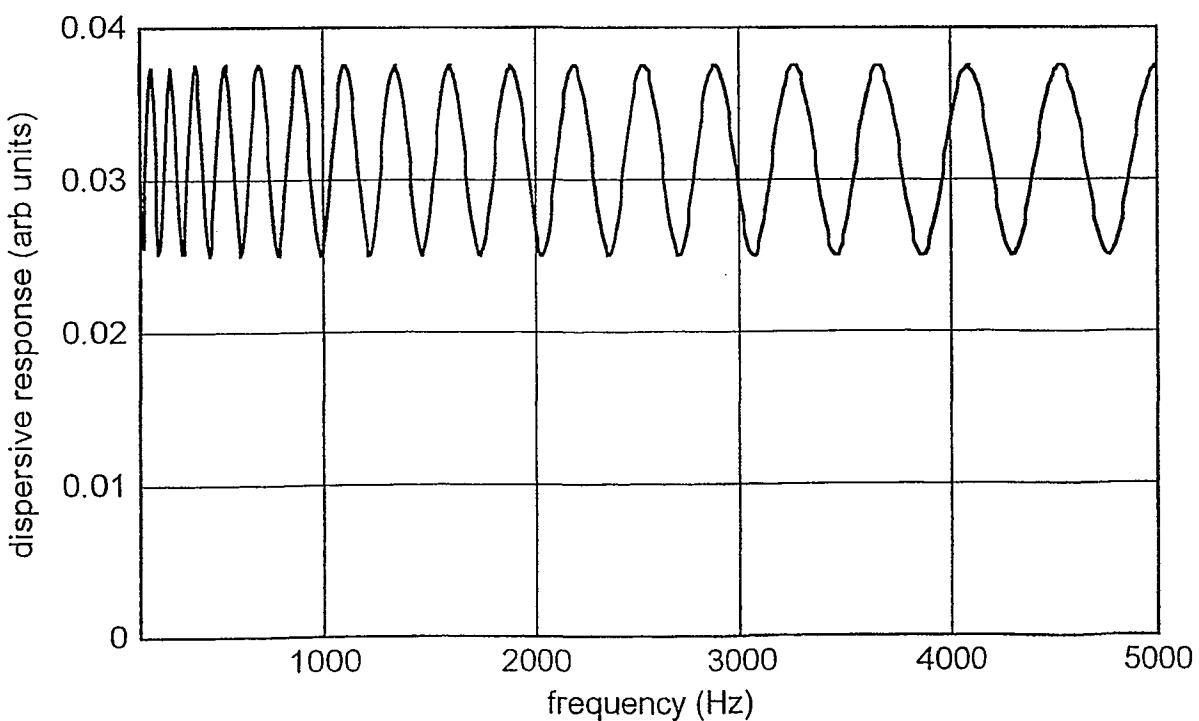
51. A contact sensitive device according to claim 50, wherein  
5 the device cycles between resting in passive sensing mode when no contact is detected, switching to active mode sensing when a contact is applied and returning to passive sensing mode once the contact is removed to wait for further contacts.

1 / 14



Graph of a dispersive impulse response

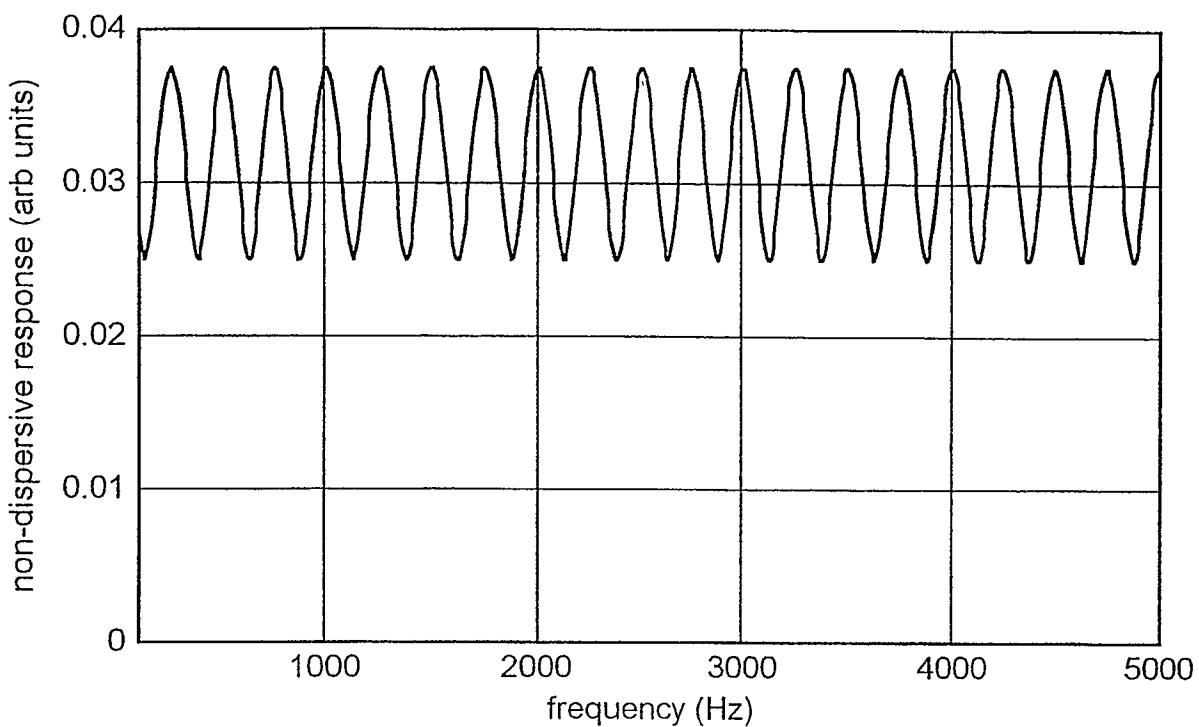
FIG. 1a



Graph of a dispersive frequency response

FIG. 1b

2 / 14



Graph of a non-dispersive frequency response

FIG. 1c

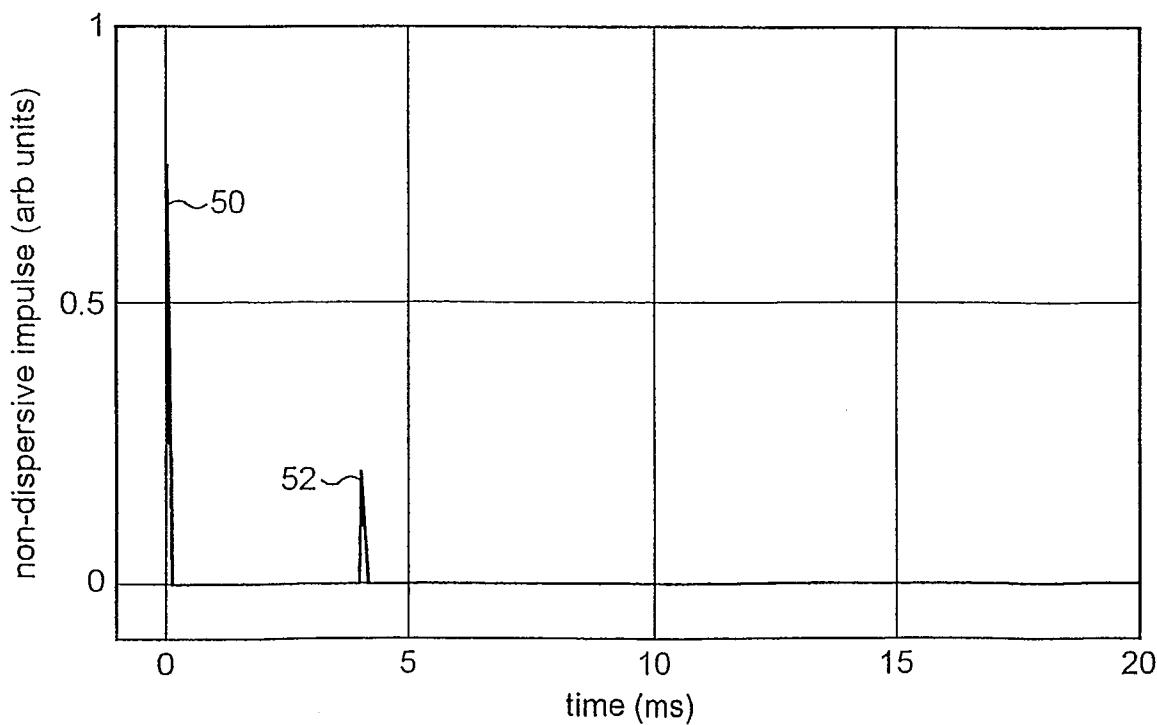


FIG. 1d

3 / 14

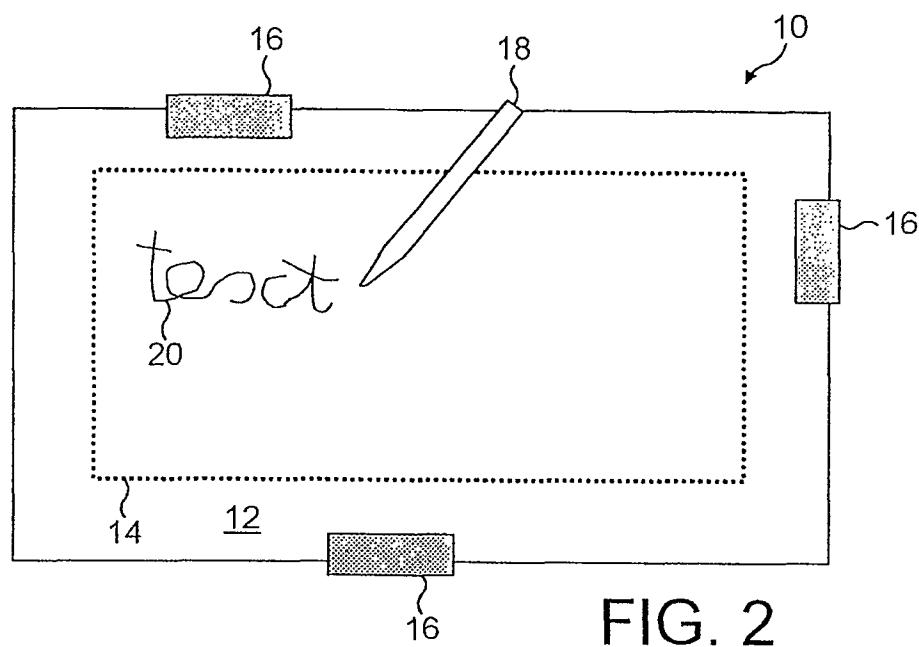


FIG. 2

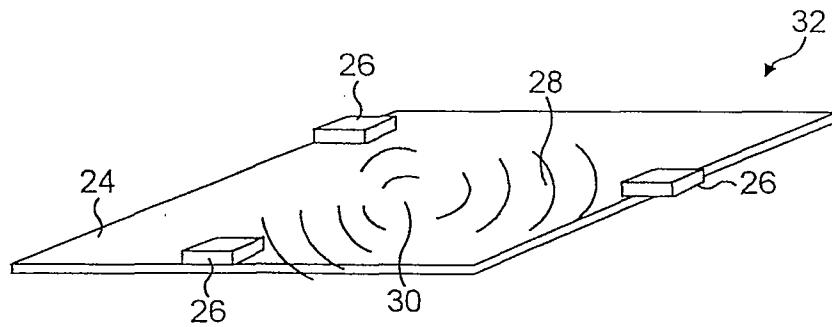


FIG. 3

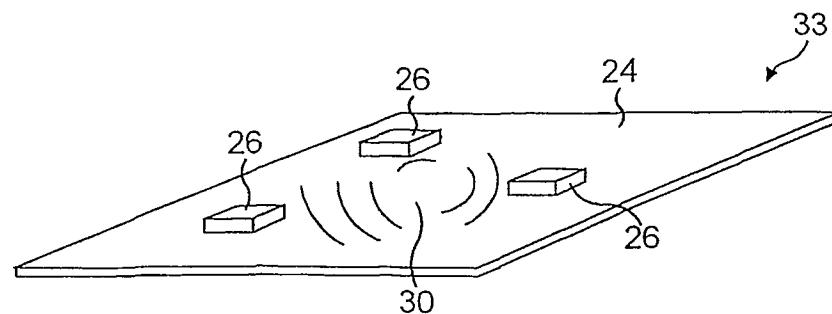


FIG. 4

4 / 14

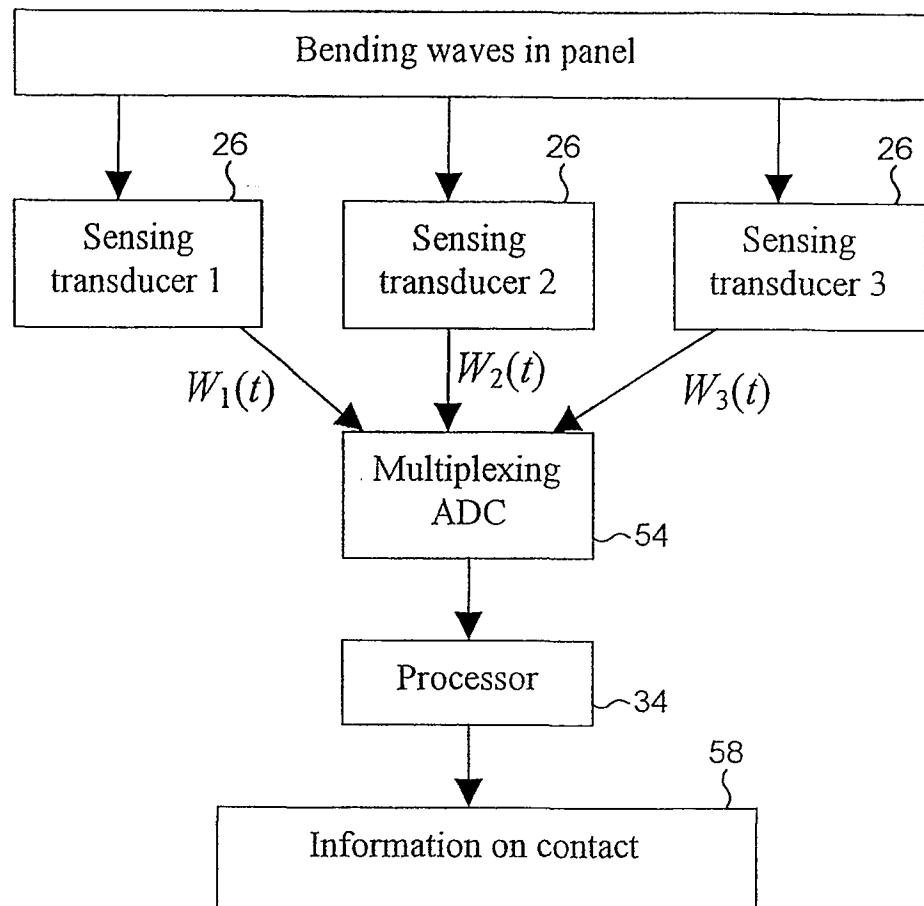


FIG. 5

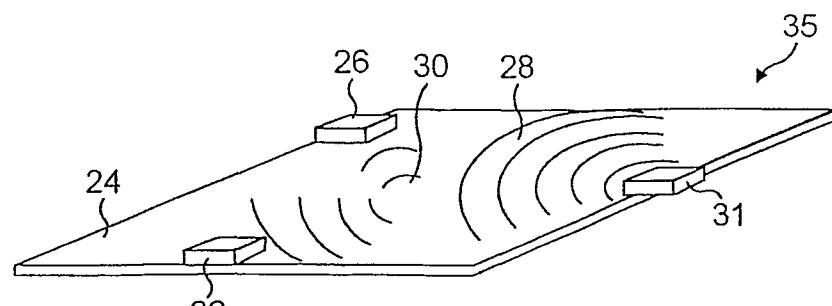


FIG. 6

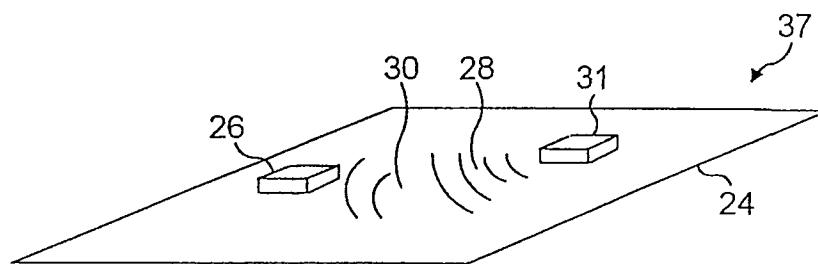


FIG. 7

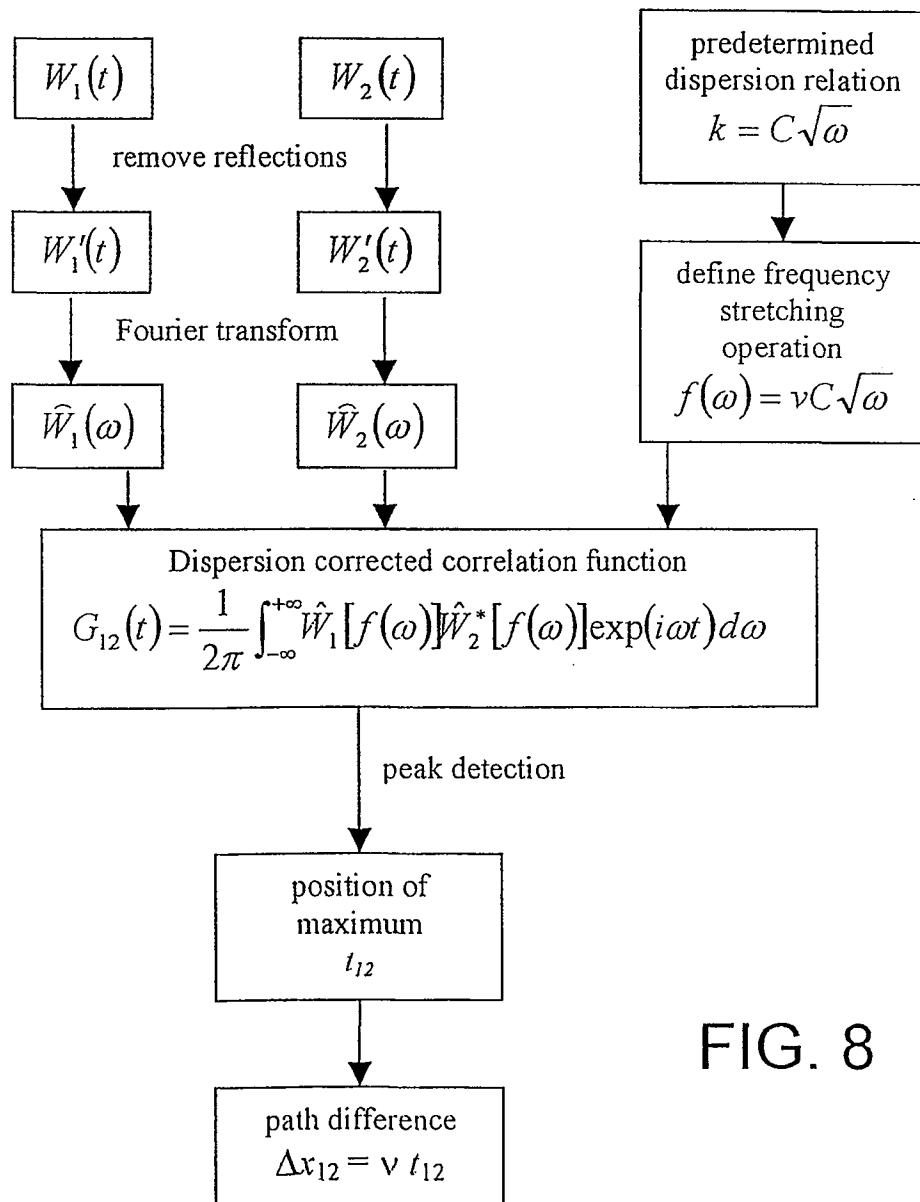


FIG. 8

6 / 14

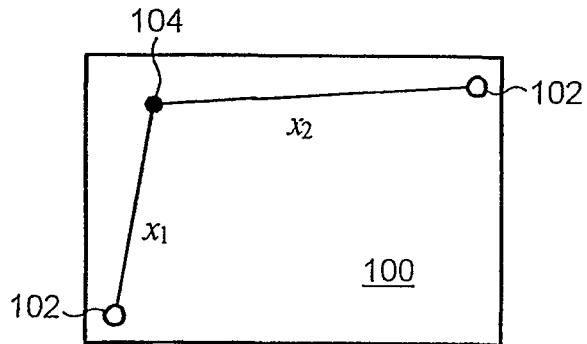


FIG. 8a

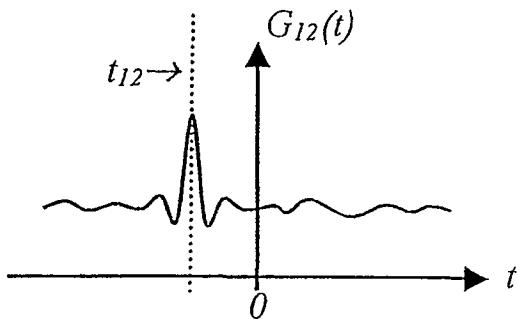


FIG. 8b

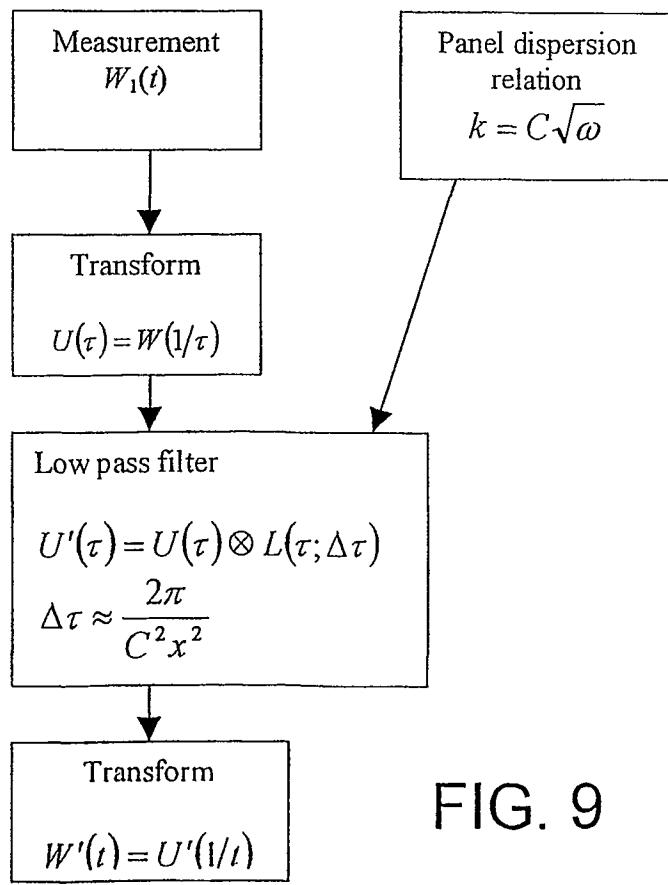


FIG. 9

7 / 14

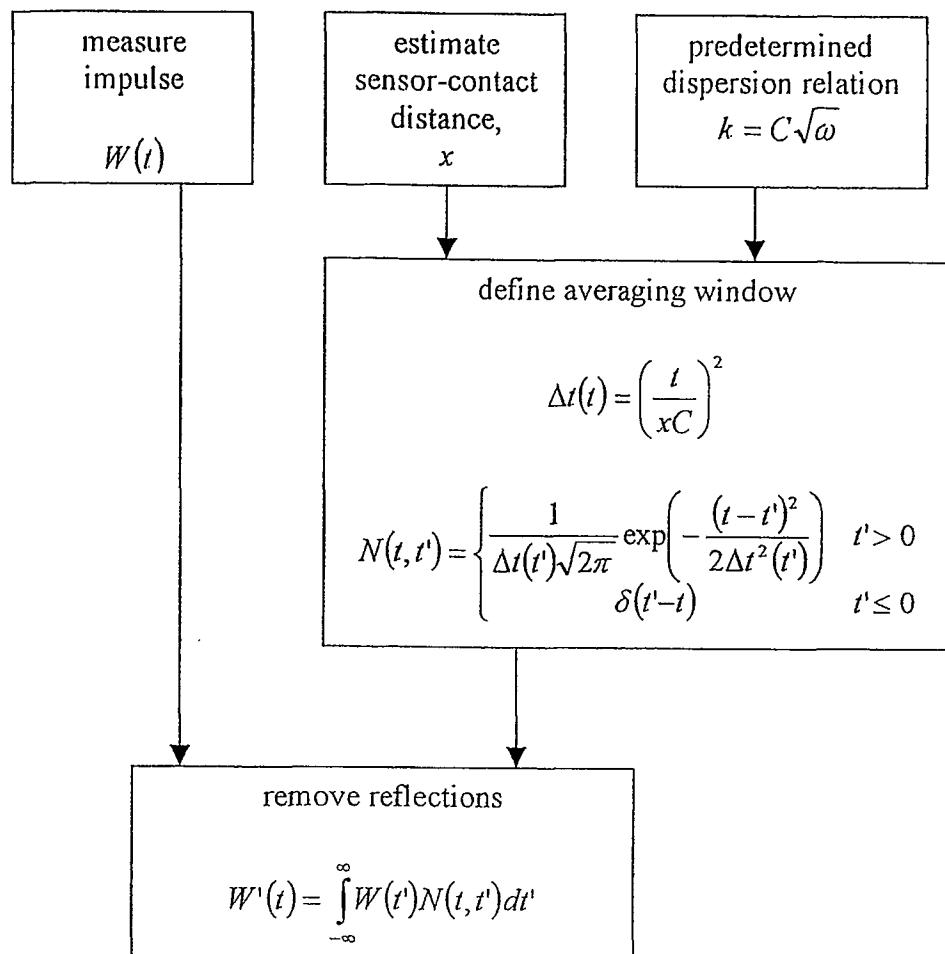


FIG. 10

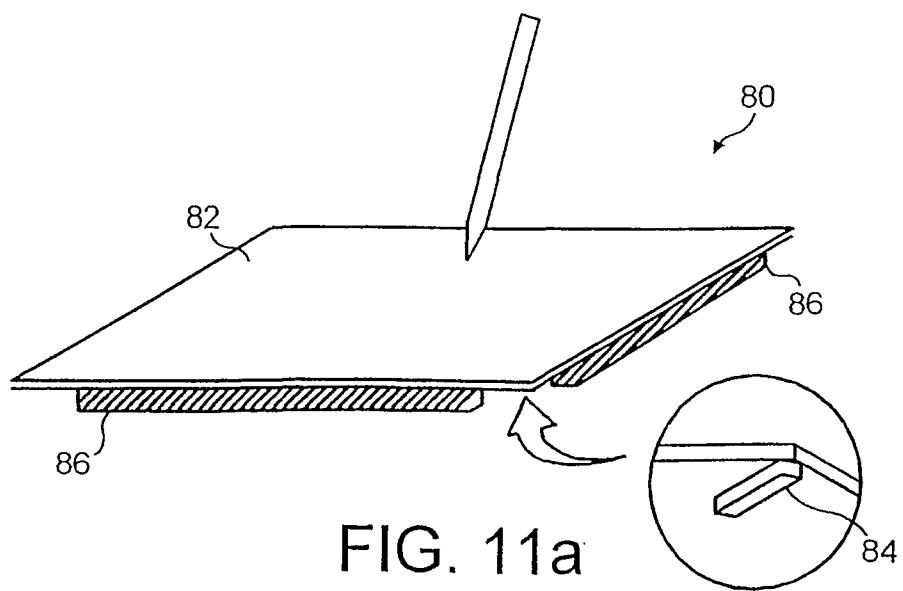


FIG. 11a

8 / 14

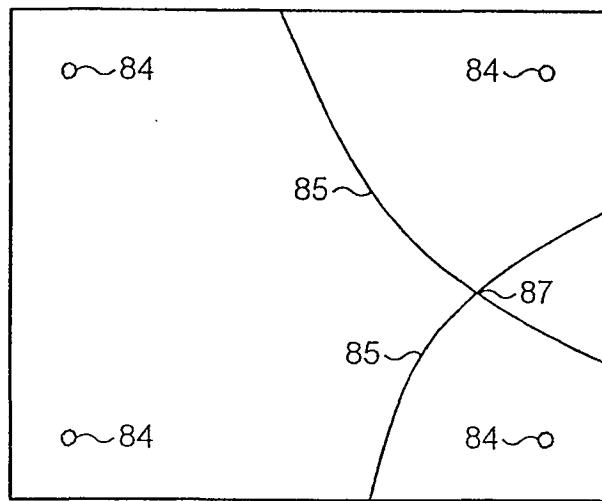


FIG. 11b

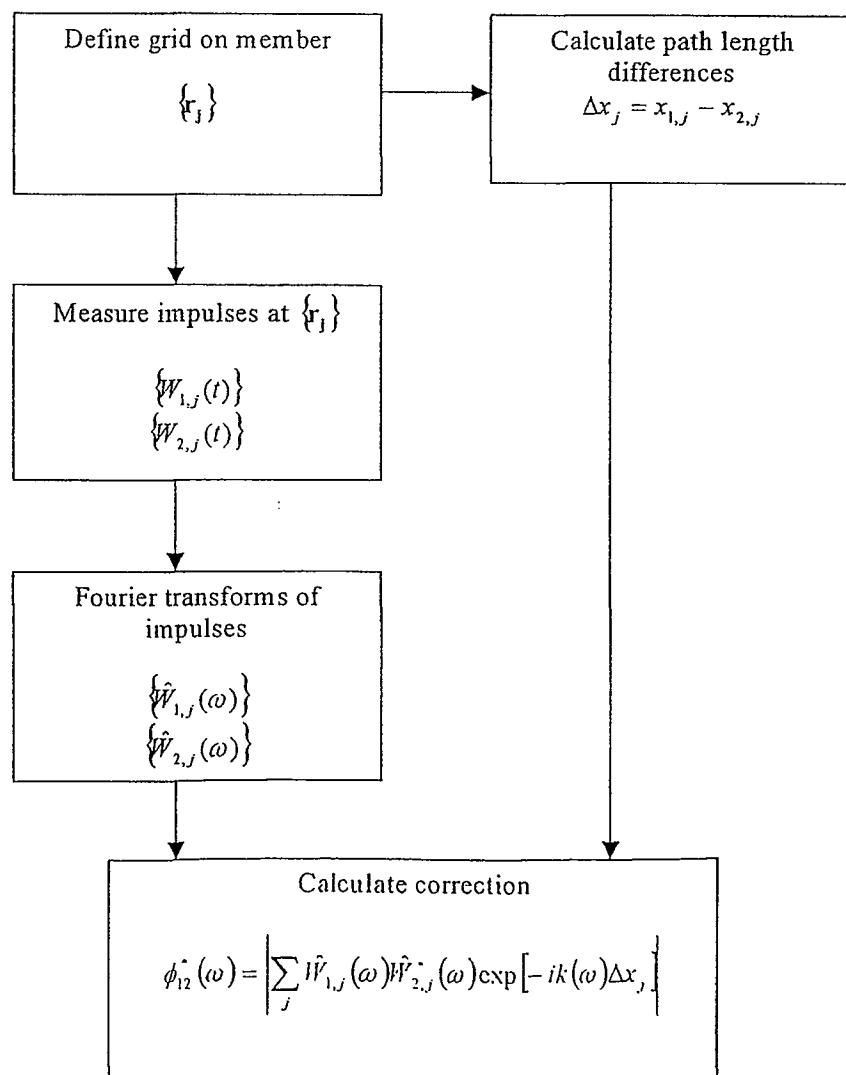


FIG. 13

9 / 14

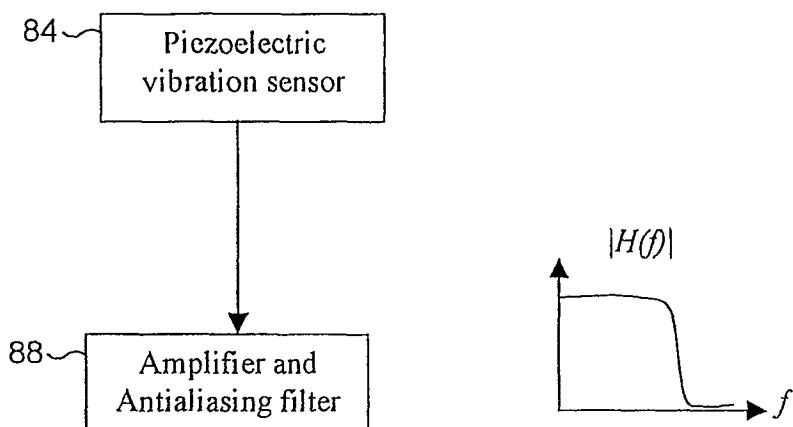


FIG. 12a

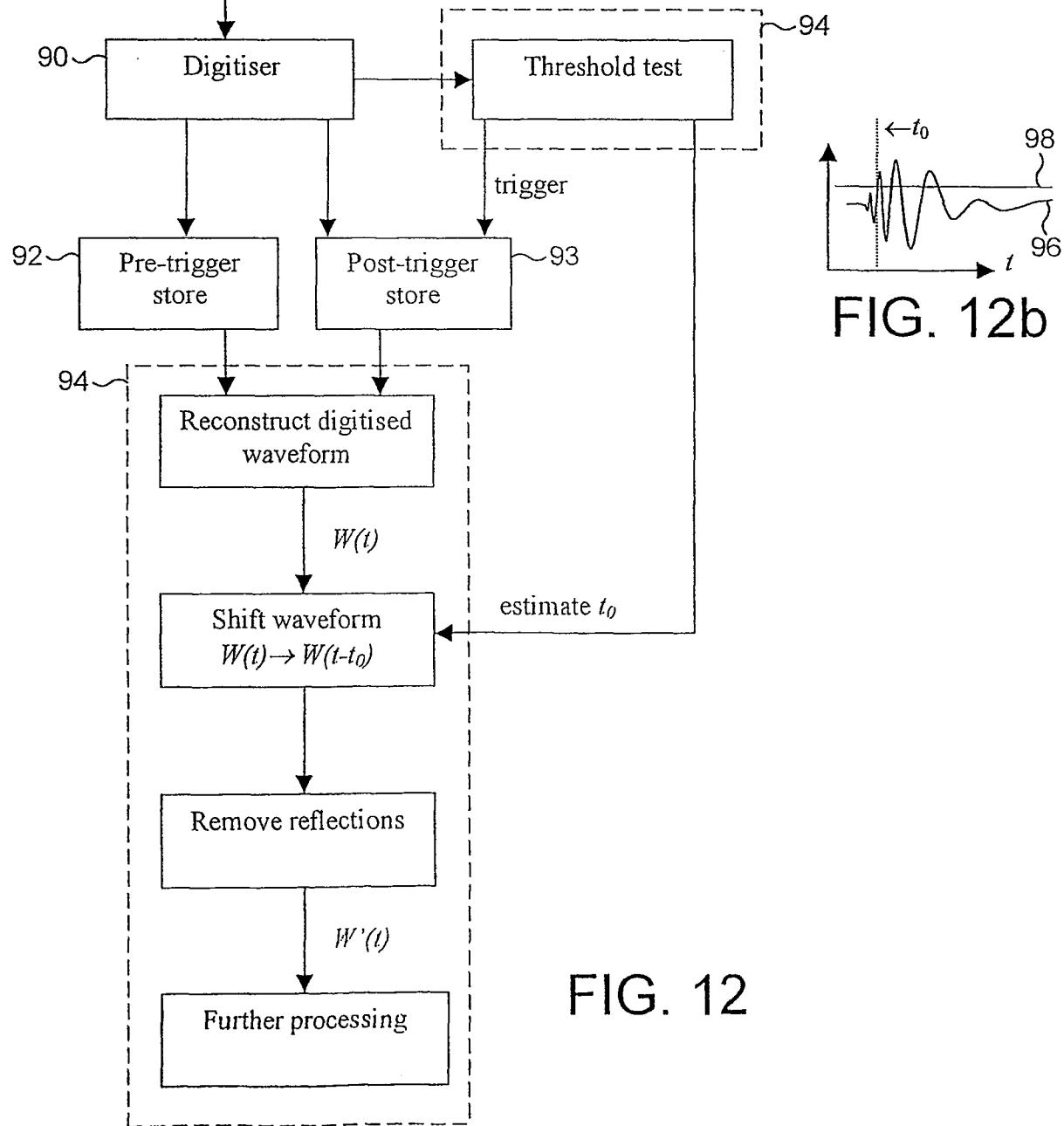


FIG. 12

10 / 14

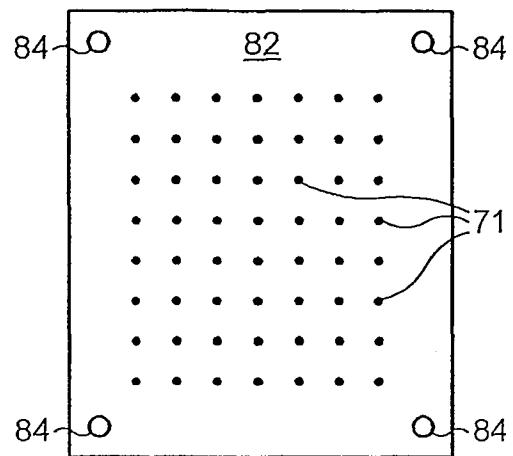


FIG. 13a

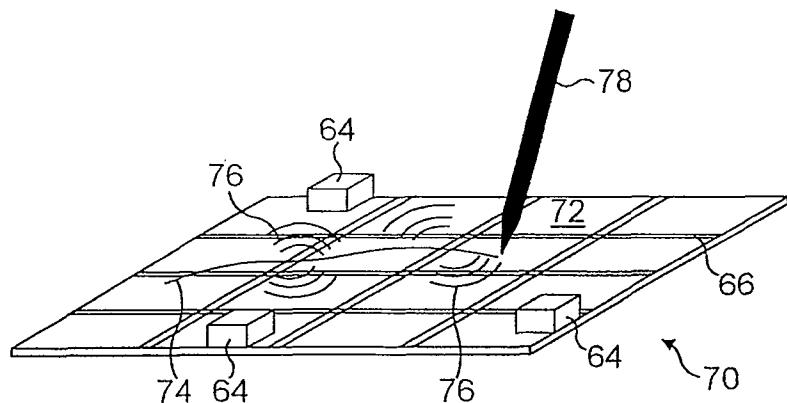


FIG. 14

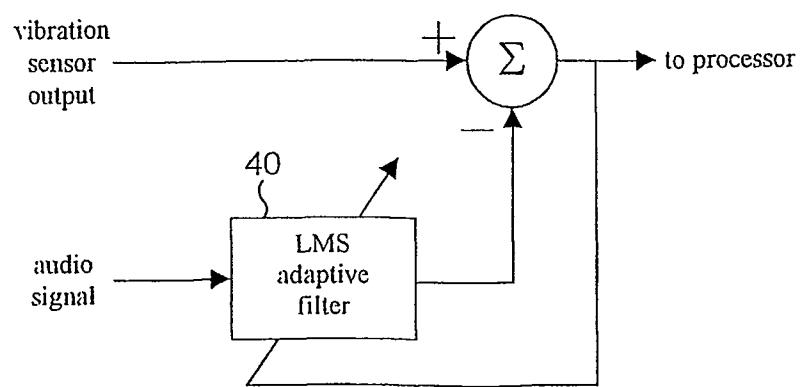


FIG. 15

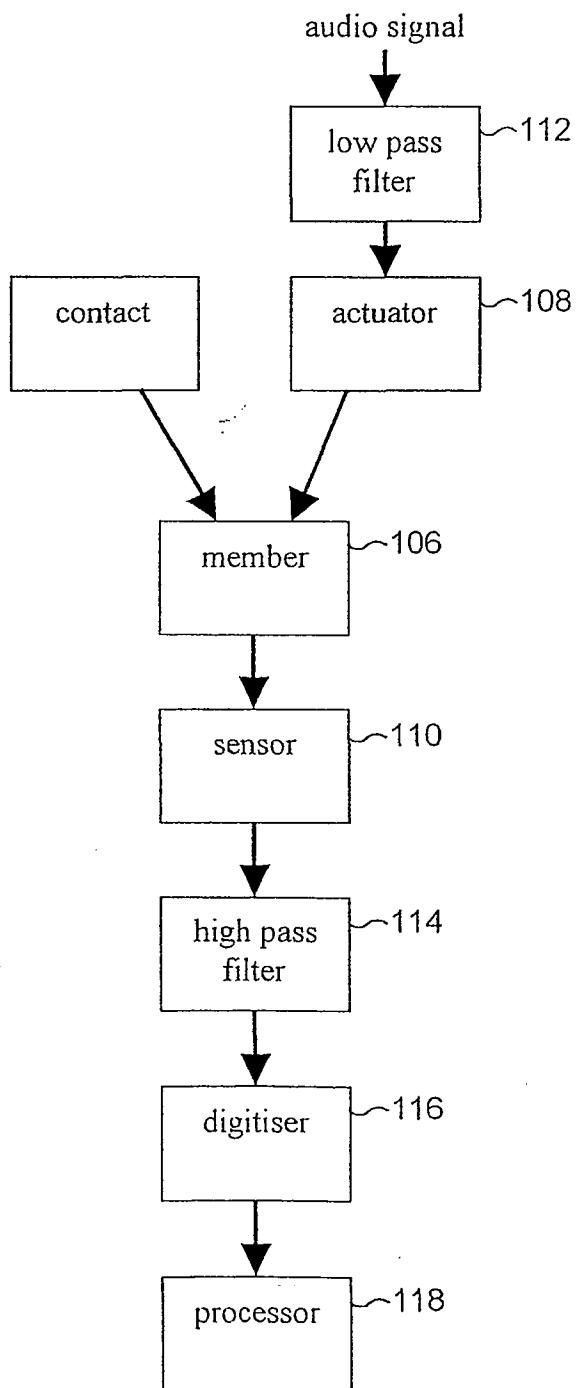


FIG. 16a

12 / 14

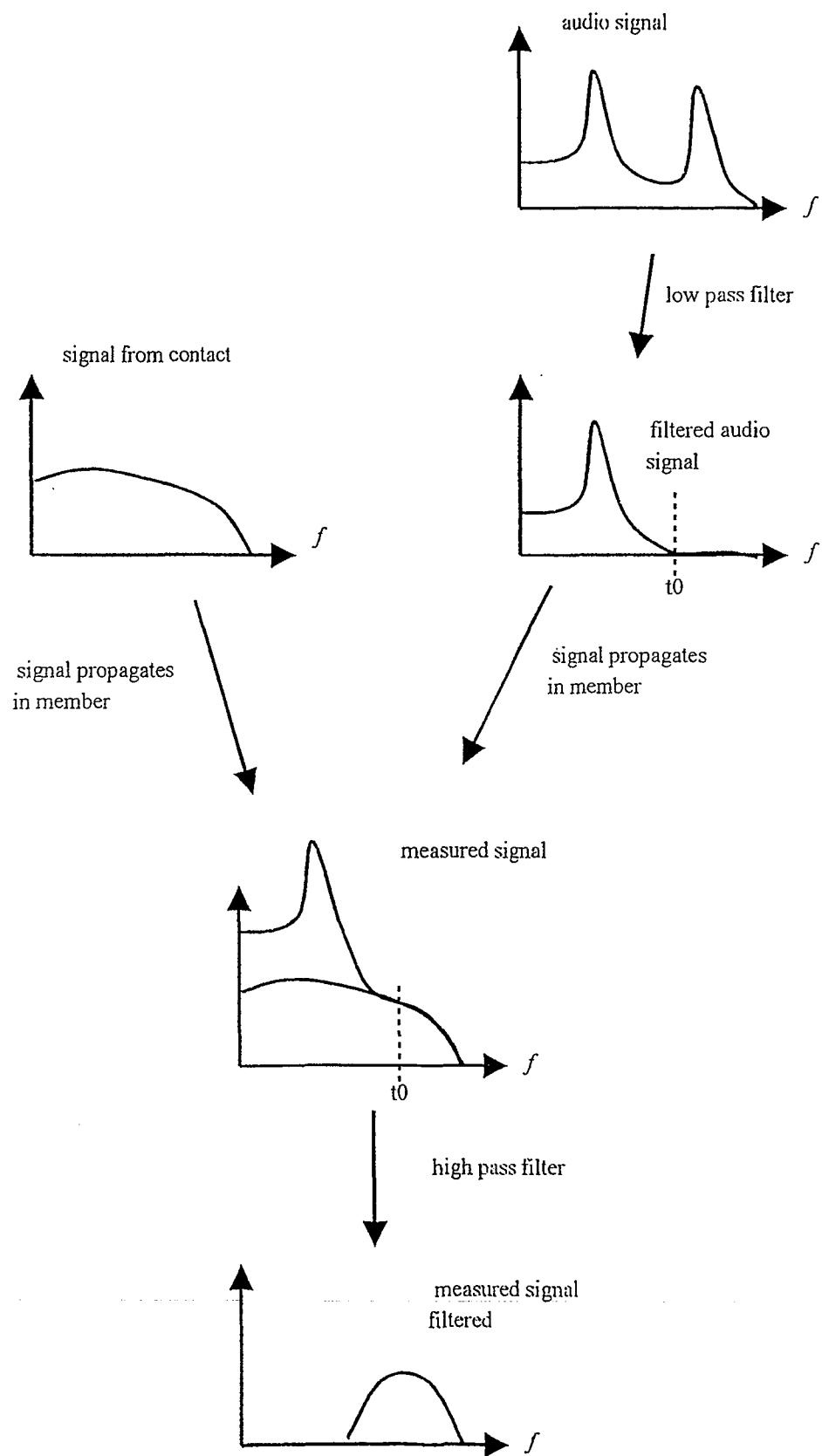


FIG. 16b

13 / 14

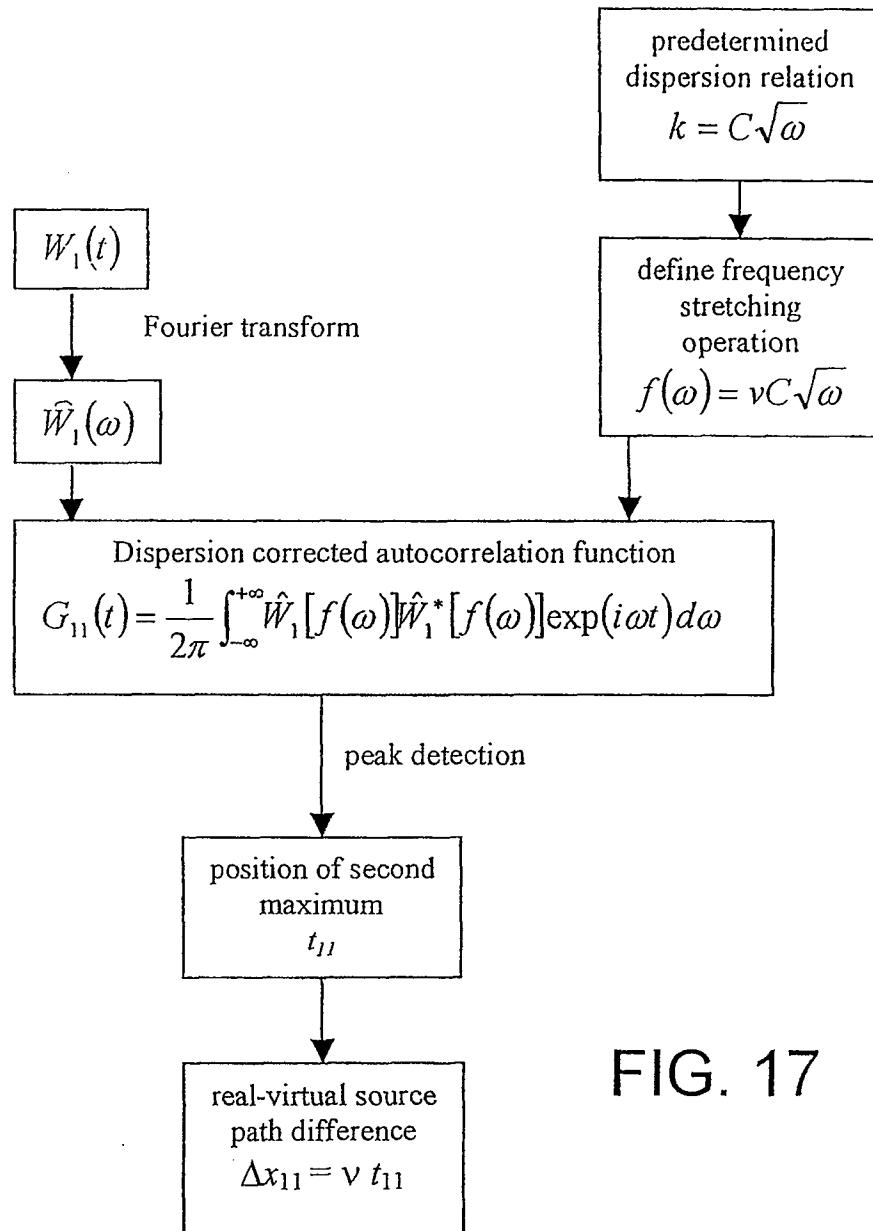


FIG. 17

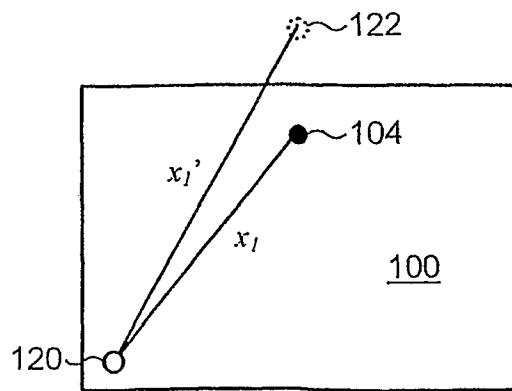


FIG. 17a

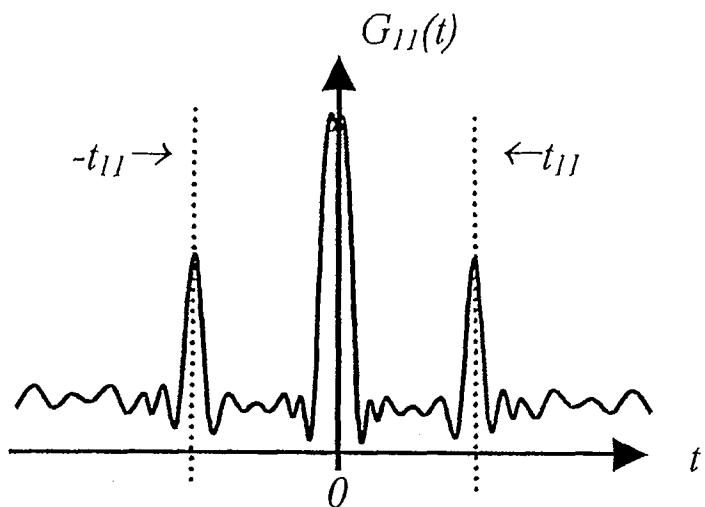


FIG. 17b

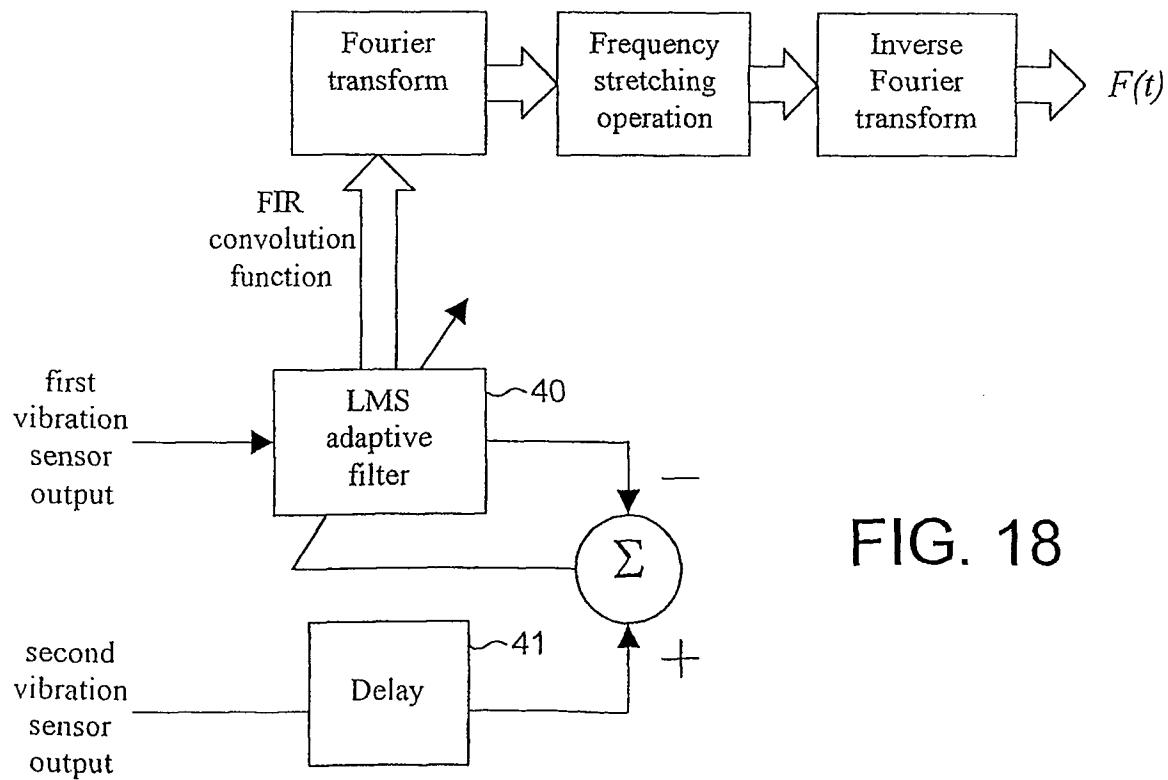


FIG. 18

A. CLASSIFICATION OF SUBJECT MATTER					
IPC 7 G06K11/14 G06K11/18		G01S5/30		G01B17/00 G06F3/033	
According to International Patent Classification (IPC) or to both national classification and IPC					
B. FIELDS SEARCHED					
Minimum documentation searched (classification system followed by classification symbols)					
IPC 7 G06K G01S G01B G06F					
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched					
Electronic data base consulted during the international search (name of data base and, where practical, search terms used)					
EPO-Internal, WPI Data					
C. DOCUMENTS CONSIDERED TO BE RELEVANT					
Category <sup>a</sup>	Citation of document, with indication, where appropriate, of the relevant passages			Relevant to claim No.	
X	US 5 691 959 A (CUMMINS JAMES D ET AL) 25 November 1997 (1997-11-25) column 6, line 6 - line 29; figures 5,6 abstract ---			1-51	
X	US 5 986 224 A (KENT JOEL) 16 November 1999 (1999-11-16) column 23, line 57; figures 13,14,31 abstract ---			1-51	
X	US 5 591 945 A (KENT JOEL) 7 January 1997 (1997-01-07) abstract; figures ---			1-51	
X	US 4 393 268 A (GUEDJ RICHARD ET AL) 12 July 1983 (1983-07-12) column 3, line 8 - line 11 ---			44-51	
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C.			<input checked="" type="checkbox"/> Patent family members are listed in annex.		
<p><sup>a</sup> Special categories of cited documents :</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&amp;" document member of the same patent family</p>					
Date of the actual completion of the international search			Date of mailing of the international search report		
24 October 2002			05/11/2002		
Name and mailing address of the ISA			Authorized officer		
European Patent Office, P.B. 5018 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016			Heusler, N		

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 856 820 A (WEIGERS DAVID G ET AL) 5 January 1999 (1999-01-05) the whole document ----	1-51
P,X	US 2001/006006 A1 (HILL NICHOLAS P R) 5 July 2001 (2001-07-05) the whole document ----	1-51
P,X	WO 01 48684 A (NEW TRANSDUCERS LTD; HILL NICHOLAS PATRICK ROLAND (GB)) 5 July 2001 (2001-07-05) cited in the application page 25; figure 6 -----	1-51

Patent document cited in search report		Publication date		Patent family member(s)		Publication date
US 5691959	A	25-11-1997	DE JP	19510908 A1 8036456 A		12-10-1995 06-02-1996
US 5986224	A	16-11-1999	US US AU AU CA EP JP JP KR WO	5854450 A 5591945 A 691094 B2 4928796 A 2214119 A1 0823108 A1 2936210 B2 10506737 T 261353 B1 9633479 A1		29-12-1998 07-01-1997 07-05-1998 07-11-1996 24-10-1996 11-02-1998 23-08-1999 30-06-1998 01-07-2000 24-10-1996
US 5591945	A	07-01-1997	AU AU CA EP JP JP KR WO US US	691094 B2 4928796 A 2214119 A1 0823108 A1 2936210 B2 10506737 T 261353 B1 9633479 A1 5986224 A 5854450 A		07-05-1998 07-11-1996 24-10-1996 11-02-1998 23-08-1999 30-06-1998 01-07-2000 24-10-1996 16-11-1999 29-12-1998
US 4393268	A	12-07-1983	FR CA EP	2483072 A2 1167819 A1 0042313 A1		27-11-1981 22-05-1984 23-12-1981
US 5856820	A	05-01-1999	JP	8263208 A		11-10-1996
US 2001006006	A1	05-07-2001	AU BR EP WO	2200801 A 0016706 A 1240617 A2 0148684 A2		09-07-2001 24-09-2002 18-09-2002 05-07-2001
WO 0148684	A	05-07-2001	AU BR EP WO US	2200801 A 0016706 A 1240617 A2 0148684 A2 2001006006 A1		09-07-2001 24-09-2002 18-09-2002 05-07-2001 05-07-2001